PB81-104796

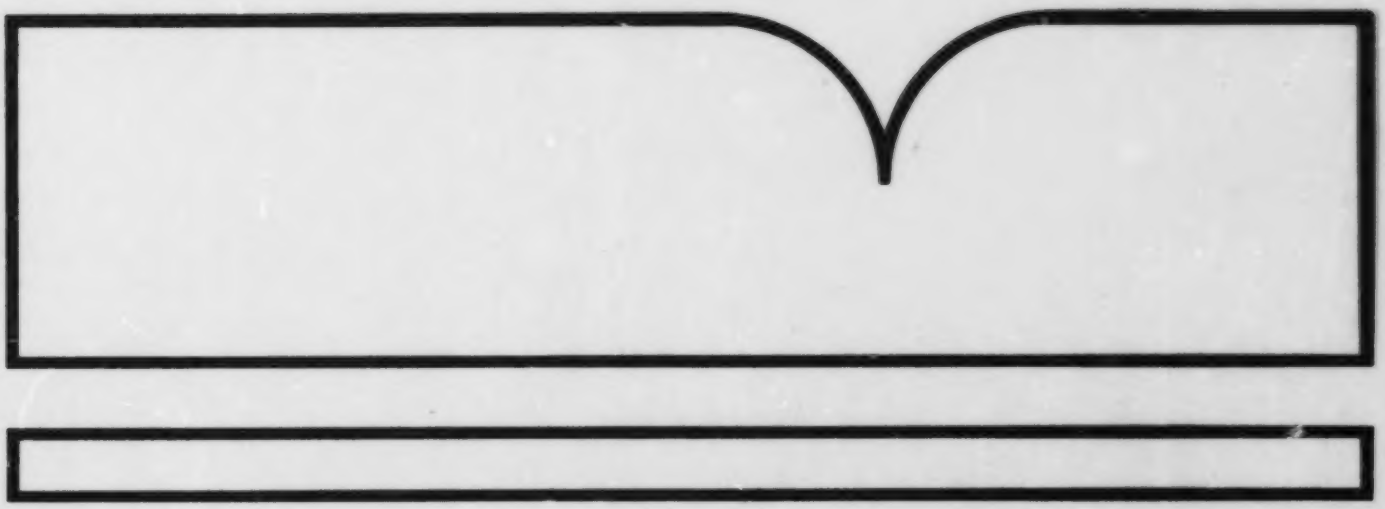
Porous Pavement. Phase I
Design and Operational Criteria

Austin, TX

Prepared for

Municipal Environmental Research
Lab.-Cincinnati, OH

Aug 80



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EPA-600/2-80-135
August 1980

Research and Development

PB81-104796

EPA

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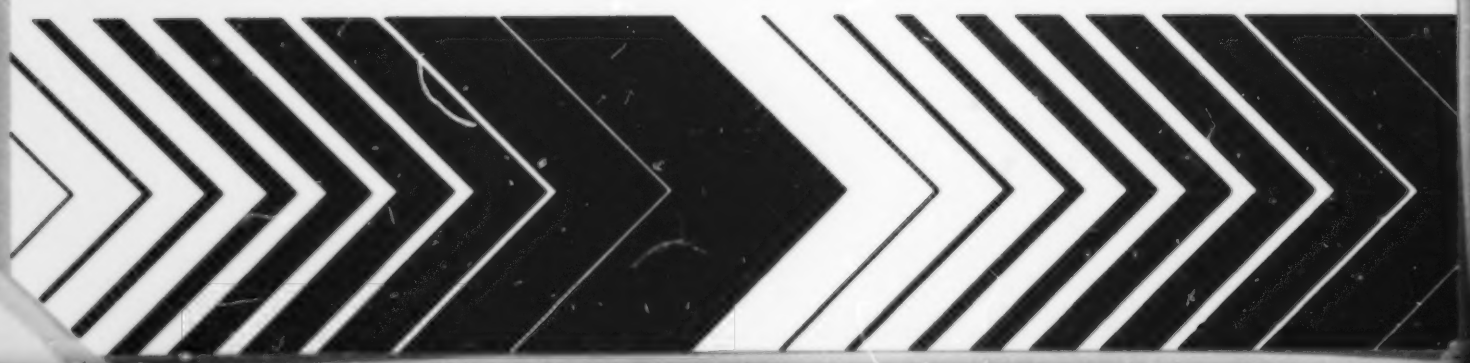

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TECHNICAL REPORT DATA
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1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-80-135		PB81 104796

4. TITLE AND SUBTITLE	5. REPORT DATE
Porous Pavement; Phase I Design and Operational Criteria	August 1980 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Elvidio V. Diniz	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS City of Austin P.O. Box 1088 Austin, Texas 78767	10. PROGRAM ELEMENT NO. 35 B1C, Task No. 415225 11. CONTRACT/GRANT NO. R806338
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., Oh Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED Final, 2/1/79 - 8/1/79 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer: Hugh Masters (201)321-6678, FTS 340-6678

16. ABSTRACT

Design and operational criteria, utilization concepts, benefits and disadvantages, as well as other characteristics of porous pavements are presented in this report. Particular emphasis is placed on porous asphalt pavements, but the criteria and design approach are applicable to all other porous pavement types.

The design considerations presented in this report include siting problems, load bearing design, and hydrologic design. A brief history of porous pavement development and previous experience with porous pavement by several designers, contractors, and operators are described.

A computer model for hydrologic performance evaluation of existing or proposed porous pavement systems is also described in this report. Load bearing design criteria are based on previous work conducted for porous asphalt pavements.

Appendices to this report include a sample set of specifications for porous asphalt construction and a list of soils and their permeability classes as prepared by the U.S. Soil Conservation Service.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pavements, Pavement bases, Porous materials, Asphalt pavements, Urban land use, Urban planning, Design criteria	Porous pavements, Urban runoff control, Asphalt concrete	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (Rev. 4-77)

o U.S. GOVERNMENT PRINTING OFFICE 1980-657-165/0142

EPA-600/2-80-135
August 1980

POROUS PAVEMENT
PHASE I - DESIGN AND OPERATIONAL CRITERIA

BY

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Grant No. R806338

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This study was conducted in cooperation with
The City of Austin, Texas

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the research and the user community.

The development of porous pavement is a recognition of the interplay between two components of our physical environment—water and earth. Porous pavement utilization attempts to sustain physical processes ongoing under natural conditions. A reorientation of urban land use from exclusion of infiltration of surface water to enhancement of infiltration can be successful with regard to both the short and long term impact of urban development.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

The overall objective of this research was to determine factors which influence runoff and water quality from areas using various porous pavement designs. The resulting information will be used to develop design criteria for potential porous pavement construction.

The first phase of this project, as reported herein, was to accumulate all available design, construction, and operational data for existing porous asphalt pavement areas. This report summarizes these data. Phase II of this project will compare the runoff and water quality characteristics of porous pavement to other kinds of conventional and experimental paving materials. Phase II results will be presented in a separate report.

Porous asphalt pavement consists of a relatively thin course of open graded asphalt mix over a deep base made up of large size crushed stone aggregate. The open graded asphalt mix has a minimum of fines (two percent or less passing the Number 200 sieve) and consequently forms a porous matrix for water to pass through to the gravel base and underlying ground. The water can be stored in the voids between the large gravel in the base material until it can percolate into the subbase or be drained through lateral drainage schemes. In this way, peak runoff to storm sewers or drainage channels can be reduced, ground water recharge is enhanced, and the cost of drainage improvements is reduced. The major cost reduction is a result of the elimination of curbs, drains, and storm sewers which are required under conventional drainage design. Additionally, storm water pollution and flooding can be reduced or eliminated.

Other porous pavement types include concrete lattice blocks with grass growing in the interstices (grasscrete) and a concrete mix with sufficient air voids to make it porous.

The development of porous pavement is an efficient combination of two existing highway drainage practices--open graded asphalt mix sealcoats and open graded crushed stone bases. However, the installation of porous pavement is possible only on well drained soils or soils provided with additional relief subsurface drainage.

Previous experience with porous pavement by various designers, contractors, and operators, has been evaluated and reduced to specific design and operational criteria which are presented herein. A set of sample specifications is included in Appendix A to this report.

A brief discussion of the advantages, as well as, the disadvantages of porous pavement utilization, a brief history of the development and previous uses of open

graded asphalt friction courses, and a generalized computer program applicable to the design of all porous and non-porous parking areas are included in this report.

This report is submitted in fulfillment of Grant Number R806338 by Espey, Huston and Associates, Inc. working under a subcontract with the City of Austin, Texas. This project is sponsored by the United States Environmental Protection Agency. The report covers the period February 1, 1979 to August 1, 1979, and work was completed as of the latter date.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CBR	--California Bearing Ratio
cm	--centimeter
EAL	--equivalent axle load
FHWA	--Federal Highway Administration
ha	--hectare
kg	--kilogram
km	--kilometer
kPa	--kilopascal
m	--meter
m^2	--square meter
m^3	--cubic meter
mm	--millimeter
MT	--metric ton
NAVFAC	--Naval Facilities Engineering Command
O_{evap}	--evaporative outflow
O_{hors}	--horizontal outflow
O_{vert}	--vertical outflow
USEPA	--U.S. Environmental Protection Agency
WES	--U.S. Army Corps of Engineers Waterways Experiment Station

SYMBOLS

a	--cross sectional area of surface water
A	--cross sectional area of flow element
C	--input weir coefficient
E	--instantaneous evaporation
E_p	--peak evaporation rate
E_t	--total daily evaporation
h_o	--depth of dead surface storage on porous pavement
h_1	--depth of surface water at time t_1
h_2	--depth of surface water at time t_2
H	--depth of flow
ΔH_i	--change of water depth at boundary
i	--rainfall intensity

I	--inflow into the reservoir
k	--lumped coefficient for effects of slope and flow retardance
K	--permeability of flow element
l	--length of overland flow
L	--input weir length
N	--input roughness coefficient
O	--outflow from the reservoir
P	--pavement perimeter
q	--flow rate per unit width
q_e	--equilibrium flow
Q	--total mass flow rate
s	--input energy slope
S	--coefficient of storage of aquifer
Δt	--time increment
t_1	--beginning time of time increment
t_2	--ending time of time increment = $t_1 + \Delta t$
t_a	--time after rainfall has ceased
t_e	--time to equilibrium
t_c	--clock time
T	--aquifer transmissivity
v	--velocity of flow
V	--volume of aggregate
V_e	--equilibrium surface detention volume
V_o	--surface detention volume
w	--width of flow
W	--total weight of surfacing mixture
Y	--computed depth of flow

ACKNOWLEDGMENTS

The cooperation of the City of Austin, Texas, Engineering Department, is gratefully acknowledged. Mr. Charles Graves, City Engineer, provided grant supervision and project guidance, and Mr. Richard Halstead maintained fiscal control over the grant. I am particularly indebted to Mr. Troy Ulmann and Mr. Ramon Miguez of the Watershed Management Section, for their cooperation, active support, and sustained interest in the project.

Information on the development and initial application of porous pavement was supplied by Mr. Edmund Thelen and Mr. Richard Hollinger of the Franklin Institute Research Laboratories, Mr. Albert Iamurri of Mirick Pearson Ilvonen Batcheler, Mr. Joachim Tourbier of the University of Pennsylvania, Mr. Douglas P. Lloyd of New Castle County, Delaware, Mr. Leonard Cannatelli of the University of Delaware, Mr. Otto Fischer of the Klett Organization, Mr. G. F. Haack of the Department of Housing and Construction, Perth, Australia, and Mr. Walter R. Hunzicker of Zurich, Switzerland. All of the information and support provided by these individuals is sincerely appreciated.

This project was conducted under the supervision of Dr. William Espey, Jr. and Mr. Joseph Beal. Data compilation and reduction were performed by Mr. Billy Goolsby and Mr. Craig Horton. Dr. Brent Rauhut provided guidance for porous asphalt structural design and also developed the sample specifications presented herein.

I would also like to acknowledge Mr. Richard Field, Chief, Storm and Combined Sewer Section and Mr. Hugh Masters, U.S. Environmental Protection Agency Project Officer, for their cooperation, guidance and assistance on this project.

SECTION I

INTRODUCTION

Porous asphalt pavement is one alternative solution to the problem of stormwater drainage from parking and other low traffic density areas. In operation, this type of pavement allows incipient rainfall and local runoff to soak through the pavement surface course of open graded asphalt concrete mix and accumulate in a porous base consisting of large open graded gravel from which the water would percolate into the natural ground below, if this is possible, or would drain laterally to a sump or channel.

The October 11, 1973 issue of Engineering News Record Magazine editorialized on porous pavement development. Part of this editorial follows:

> "Instead of pavements built of carefully graded materials topped and sealed to be waterproof, porous soils might just as well carry porous pavements. Let rainfall run through rather than run off. Save the cost of curbs, gutters, drains, collectors, storm sewers, receiving basins. And get a good skid resistant pavement surface in the process.
>
> The idea has a freshness and simplicity about it. And if there are flaws, they should be found in tests at experimental installations, existing and planned. But we'll be surprised if the construction industry does not grab this idea and run with it without waiting for the full findings of tests. The only real danger can be misapplication, use of the pavement on soils that are not suited for it, not porous."

In regular applications for highway and airport runway construction, the open graded asphalt concrete mix has variously been referred to as plant mix seal coat, open graded mix, gap graded mix, popcorn mix, or porous friction course. This material consists of an open graded asphalt concrete mixture with a high percentage by weight of aggregate larger than a Number 4 sieve. The material is laid to a thickness of 3/4 to 1 inch (1.91-2.54 cm). The resulting pavement has a coarse surface texture and a high void ratio. The coarse surface texture provides pressure relief channels to remove water under excess pressure between the pavement and a vehicle tire. Also, the high void ratio provides channels for dissipation of pressure and flow beneath the vehicle tire. Finally, the high void ratio also provides temporary storage for surface water. Consequently, hydrostatic pressure cannot build up in the film of surface water under a vehicle tire and hydroplaning potential is eliminated. Conjunctively, the coefficient of friction between the tire and pavement is almost equivalent to the coefficient under dry conditions.

The highway departments of California, Nevada, New Mexico, Utah and Louisiana have been using plant mix seal coats because of their safety aspects for at least the past 10 years. Application of this material to airport runways was initiated in 1967 at Farnborough, England by the British Royal Air Force, and two European air fields by the United States Air Force. Since 1947, the California Highway Department has utilized open graded base courses under conventional top paving to provide rapid drainage in problem areas.

In 1971, Franklin Institute Research Laboratories, under United States Environmental Protection Agency (USEPA) sponsorship, investigated the use of a porous base and a porous subbase in conjunction with a thicker application of the plant mix seal coat (1). The intent of this experiment was to investigate the potential of delivering water to the subbase rather than removing it to a storm water collection system. Initial installations in Delaware and Pennsylvania (2) proved successful and subsequent installations in Texas (3) have been scientifically instrumented and monitored.

Currently, each porous pavement design is unique; therefore, it is evaluated and permitted by regulatory agencies only after a long analysis and review period. This report is prepared in an attempt to standardize the design approach and yet allow the designer sufficient latitude for individual creativity. It is expected that the data presented in this report may be sufficient to design simple parking areas and residential streets. However, for complex conditions, a thorough analysis by qualified professionals is essential for the design of a porous pavement.

In general, potential as well as existing users and review agencies have expressed a need for data on three conditions regarding porous pavement systems. These conditions are:

1. Construction feasibility, maintenance and design life.
2. Control and management of runoff peaks and volumes.
3. Control and management of water quality degradation.

This report addresses these three issues and attempts to provide sufficient data to indicate the desirability of porous pavement parking areas as a viable means of drainage control and water quality enhancement.

The need to evaluate the runoff changes and water quality constituent changes from urbanizing activities is paramount in the design of porous pavement systems. Unfortunately, most engineering practice holds the view that all pavements have to be evaluated solely from a runoff view point. Only recently has water quality degradation become a point of concern for most practitioners and public officials. It is anticipated that as the concern for water quality of urban runoff becomes recognized, the need for porous pavement parking systems will increase.

The study reported herein investigated all of the available data from existing porous pavement sites. This data included the engineering design, hydrology, pavement design, construction methods, operation and maintenance of the site and problems encountered in construction and maintenance. All of this information was condensed in Tables 1, 2, and 3, and personal observations were added where appropriate. However, the only scientifically instrumented porous pavement area is at The Woodlands site in Texas (USEPA Grant No. S802433). This data compilation should prove useful in evaluating the need for and designing porous pavements in other areas of the United States.

The list of existing porous pavement areas presented in Table 1 is not comprehensive and only indicates those areas for which data were readily available. Numerous other porous pavement areas have been designed and constructed, but researching these was beyond the scope of this study.

TABLE 1

EXISTING POROUS PAVEMENT AREAS

Number	Location
1A	South College Avenue Parking Lot. Newark, Delaware
1B	Orchard Road Parking Lot. Newark, Delaware
2	Marine Sciences Center. Lewes, Delaware
3	Woodlands, Texas
4A	Bryn Mawr Hospital. Bryn Mawr, Pennsylvania
4B	Bryn Mawr Hospital, Lot No. 2. Bryn Mawr, Pennsylvania
5*	Havertown Hospital. Havertown, Pennsylvania
6*	Newton, Savings Association Parking Lot, Washington Crossing, Pennsylvania
7	Travelodge. Tampa, Florida
8*	Salisbury State College. Salisbury, Maryland
9	Powell Ford Park. New Castle County, Delaware
10*	Coney Island Housing Project. North of Nathans, New York
11*	Korman Interplex. Philadelphia, Pennsylvania
12	Bell Telephone Company, West Goshen Township, Chester County, Pennsylvania
13	Bell Telephone Company. Newtown, Pennsylvania
14	Hollywood Hospital. Perth, Australia
15	Hamersley Headquarters Telecom. Perth, Australia
16*	Zurich Hilton. Zurich, Switzerland

*Identified existing sites for which data were not available

TABLE 2

TECHNICAL DATA FOR EXISTING POROUS PAVEMENT AREAS

Porous Pavement Site	Instalation Date	Design Storm (in.)	Area (Acres)	Topography Slope %	Soil	Permeability ft./Day	Side Flow	Available Outflow	Type of Use
1A	1973	6.0	0.64	2.0	----	0.50-1.00	from North	Southwest Corner	Light Parking
1B	1974	---	1.37	---	Brown Clay, Slightly sandy, Silt	576.0	----	Northwest and Southwest corners with french drains	Light Parking
2	1974	---	5.00	---	Clay lenses,3 ft. in diameter	-----	----	----------	Parking and service Roads
3	1975	---	0.50	---	Poor, replaced w/ 3 ft. of sand	-----	----	Nearby Creek	Light Parking
4A	1975	5.0	0.75	1.4	---------	1.00	none	3-4 inch drains at subbase for each section	Parking 100 cars
4B	1977	---	0.22	3.5	---------	-----	none	----------	Parking 33 cars
7	1973	---	----	---	---------	-----	----	----------	Parking Lot
9	1974	4.4	0.93	1.8	Clay, silt, gravel, silty sands & Silty Clay	0.050 0.120 0.003	none	Catch basin & 1-12" RCCP	Parking 109 + cars
12	1977	---	2.76	2.1	Glenelg Channery Silt loam	-----	runoff from building	Retainage trench along N.W. boundary	125 employee cars, 100 company vehicles
13	1976	7.2	4.00	---	Readington Silt loam	-----	Roof drains onto pavement	Outlet stream to Newton Creek	Parking and delivery
14	1978	---	----	---	----------	-----	--------	----------	----------
15	----	---	2.29	---	Limestone sand	-----	--------	----------	Parking Lot

TABLE 2 (continued)

Porous Pavement Site	Asphalt Mix Thickness inches	Base Thickness inches	Drains Installed	Remarks/ Comments
1A	2.5	12	30 ft. trench, 15 ft. X 3 ft. L-shaped 3/4 inch stone	Asphalt was laid on hot day, trouble with rolling, trouble with trucks disturbing subbase, had to regrade.
1B	2.5	12	45 ft. trench, 15 ft. X 3 ft. L-shaped 3/4 inch stone	Northwest Corner
2	2.5	6	30 ft. trench, 15 ft. X 3 ft. 3/4 inch stone	Southwest Corner
3	2.5	12	5-4" drains to nearby creek	----------
4A	2.5	10-14	----------	Pavement Failed
4B	2.5	12	----------	6½" layers of 2" stone 5' back from end of lot
7	---	--	----------	Breakdown of asphalt by large trucks parking, water ponding
9	2.5	12	40 ft. trench 6.5 ft. X 3 ft. in end of lot	In place for 5 years, excellent condition water runs off end of lot
12	2.5	16	----------	Mud from heavy equipment plugged porous pavement lot, fork lifts gouge pavement
13	4.0	8-20	----------	----------
14	1.2 2.0	4-6	----------	Limestone base is less expensive than crushed rock
15	1.2 2.0	4-6	----------	----------

Note: 1 inch = 2.54 cm
1 foot = 30.48 cm
1 acre = 0.405 hectare

TABLE 3

OWNERS AND DESIGNERS FOR EXISTING POROUS PAVEMENT SITES

Location	Owners	Designers
1A	University of Delaware Newark, Delaware	Edward R. Bachtle, Bachtle & Associates, Inc. 111 Jefferson Street Wilmington, Delaware
1B	University of Delaware Newark, Delaware	Robert M. Lamison University of Delaware Newark, Delaware
2	University of Delaware Newark, Delaware	Robert M. Lamison University of Delaware Newark, Delaware
3	Woodlands Development Corporation Woodlands, Texas	Rice University Houston, Texas
4A	Bryn Mawr Hospital Bryn Mawr, Pennsylvania	Mr. Albert Lammurri Merick, Pearson, Illvonen, Batcheler, Architects Philadelphia, Pennsylvania
4B	Bryn Mawr Hospital Bryn Mawr, Pennsylvania	Mr. Albert Lammurri Merick, Pearson, Ilvonen, Batcheler, Architects Philadelphia, Pennsylvania
5	Havertown Hospital Havertown, Pennsylvania	----------

TABLE 3 (continued)

Location	Owners	Designers
6	Newton Savings Association Washington Crossing, Pennsylvania	----------
7	Travelodge Tampa, Florida	Leon Stone with Franklin Institute Research Laboratories as Consultant
8	Salisbury State College Salisbury, Maryland	----------
9	New Castle County, Delaware	Edward R. Bachtle, Bachtle & Associates, Inc. 111 Jefferson Street Wilmington, Delaware
10	Urban Development Corporation	----------
11	Korman Corporation Philadelphia, Pennsylvania	----------
12	Bell Telephone Company West Goshen Township, Chester County, Pennsylvania	The Klett Organization 112 York Road Jenkintown, Pennsylvania
13	Bell Telephone Company Newton, Pennsylvania	Furlow & Associates 320 Walnut Philadelphoa, Pennsylvania

TABLE 3 (continued)

Location	Owners	Designers
14	Hollywood Hospital Perth, Australia	Department of Housing and Construction
15	Australia Telephone and Telecommunications Commission, Perth, Australia	Department of Housing and Construction
16	Zurich Hilton Zurich, Switzerland	Walter R. Hunziker & Associates Zurich, Switzerland

SECTION 2

CONCLUSIONS

Porous pavements can be an effective means of reducing the increase in runoff rates and volumes, and water quality degradation, resulting from urbanization and/or other land use changes. The design of porous pavements has to be undertaken with extreme care, particularly in areas where the natural soils do not have sufficient permeability to naturally drain the stored runoff within a reasonable time.

The use of porous pavements is presently limited to parking lots only. Ideally, these parking lots should be located on soils which have very low runoff potential or which have a high percolation rate. Because all runoff from the site as well as adjacent areas are effectively retained, it may be assumed that the entire area contributing to the porous pavement has been removed from the surface hydrologic regime. Consequently, the increase in runoff rates and volumes by urbanization is offset by a reduction in drainage area.

The net downstream effect of porous pavements can range anywhere from a reduction of runoff rates and volumes to below natural levels, or to the total elimination of runoff from the immediate area. In either case, the effect downstream can be quite substantial; in the case of storm sewers, the sewer requirements may be reduced or eliminated, thereby providing substantial cost reductions; and in the case of combined sewers, the number of overflows will be reduced or eliminated, thereby providing direct benefits to the receiving water. In both cases, the cost of additional drainage facilities is reduced; and, consequently, the incremental additional cost of porous pavement systems may be recovered.

The water quality of urban runoff has been shown to be severely polluted in some instances, but in all instances the runoff is at least partly contaminated. It is obvious that just the infiltration and velocity reductions in porous pavements will result in some suspended particulate removal and some chemical pollutant reduction. Preliminary data at The Woodlands site also indicate that nutrients can be reduced to safely disposable forms and concentrations of some heavy metals can also be reduced. In any case, the removal of water from the surface runoff regime prevents the introduction of pollutants into the receiving water and creating problems in downstream areas.

If it is known, or the possibility exists, that water infiltrating into the ground could reach a water supply aquifer, adequate precautions should be taken to determine that the surface runoff is not still contaminated when it reaches the aquifer. If there is a possibility of adversely affecting the aquifer, the porous pavement area should be designed to be sealed off from the aquifer recharge zone.

If, on the other hand, the surface runoff is designed to be cleaned before it reaches the aquifer, then the infiltration of runoff into the porous paving and into the natural ground should be encouraged in order to enhance the water supply from that aquifer.

Another cost reduction can be realized in the elimination of curbs and gutters around the parking lot. Porous pavements will operate more efficiently and there is less chance of debris accumulation on the parking lot if curbs are eliminated. The removal of curbs is also aesthetically desirable.

The removal of surface water from porous pavement surfaces proves to be a distinct advantage under wet road conditions when it has been found that porous pavements are approximately 15 percent more resistant to skids. This expected result was evaluated by testing at The Woodlands, Texas site (4).

A review of the size gradations recommended by various highway authorities and the Franklin Institute Research Laboratories for composition of the aggregate in porous pavements indicates that a minimum of two percent passing the Number 200 sieve was required to provide stabilization of the coarse aggregate fraction. Consequently, the following size gradation is recommended for the open graded asphalt mix.

Sieve Size	Gradation Recommended
½"	100
3/8"	90-100
# 4	35-50
# 8	15-32
# 16	2-15
# 200	0-3

The total asphalt cement content for the mix is suggested to be between 5.5 and 6.0 percent. However, the actual percentage is a function of the source and type of aggregate. The exact percentage must be determined in the field, particularly if the characteristics of the aggregate are not known from previous experience. Also, dry aggregate should be used to avoid vapor release after the aggregate is coated. Insulated covers must be used on all loads during haul to prevent the asphalt from crusting on the surface of the load. Also, medium to light weight vibratory rollers are somewhat better for compaction of the open graded asphalt mix. A set of sample specifications is included in Appendix A to this report.

The design of porous pavement goes contrary to the classical requirements of high density and low air voids in the surface course and base course of conventional asphalt paving. Also, the idea of exclusion of water from the base course as in classical design has to be reevaluated in the case of porous pavement.

A two-inch (5.08 cm) top gravel course was found to be desirable to stabilize the top of the gravel reservoir underlying the open graded asphalt mix. The gravel reservoir is designed to control the total volume of runoff computed for the area based on a preselected design storm and a hydrologic analysis of the area. Because the length and width of the base reservoir are generally limited by the dimensions of the parking lot, the only variable dimension can be the depth. If sufficient depth cannot be obtained due to physical limits, additional relief drainage structures such as french drains and pipe drains may be installed. In this case, the cost of such structures can be quite expensive, and consequently, conventional drainage schemes may become cost-competitive and viable alternatives. If the subbase does not drain at a sufficient rate, relief drainage structures may be incorporated or additional excavation or replacement with material having more desirable drainage characteristics may be contemplated.

The total thickness of the base reservoir should be the largest depth requirement for the bearing strength of the wet subbase, the hydrologic storage requirements, or the frost depth for the site. In most cases, the hydrologic depth requirement and the bearing strength of the soil are dependent upon the area contributing to the porous pavement site; consequently, the frost depth may be the governing or limiting factor (except in the case of very weak supporting soils). A deep base may also be required to support heavy traffic loads.

The initial costs of porous asphalt can go as high as 35 to 50 percent above the cost of conventional paving. However, the major reason for this difference is the new technology involved in porous pavement production, primarily in gradation requirements and the narrow limit on asphalt cement content in the hot mix. If curbs, gutters or storm sewers are not required, the total cost of the parking lot can be comparable to or cheaper than a conventional parking lot, especially if the aggregate source for the asphalt mix as well as for the base reservoir are easily available. Therefore, it is anticipated that with the construction of additional porous pavement areas, technology transfer should be facilitated. Also, construction crews will become more familiar with the process, and contractors will be able to bid lower on porous pavement jobs.

The hydrologic design for porous pavements has been adopted onto a computer program, PORPAV, which is available as a stand-alone program or as a subroutine within the USEPA Storm Water Management Model. Both versions can be used to determine the storage requirements for a given area, size, design storm, and permeability and void ratios of the component parts and existing soil.

For most efficient operation of porous pavements it is desirable that the subbase not be compacted or be only minimally compacted. This will retain the original permeability of the soil which can be substantially reduced after compaction.

SECTION 3

RECOMMENDATIONS

The design of porous pavement parking lots is just emerging from the experimental phase. Most porous pavement users and designers would agree that further research and test demonstration pavement areas must be installed. Although existing porous pavements have performed more than adequately and have required minimal maintenance, some questions still remain. These include quantification of runoff and water quality changes, the long-term effects of continuous saturation of the subgrade, maintenance and potential for plugging, aggregate gradation and asphalt content in the hot mix, construction material types, and the economic efficiency of using this type of pavement under existing regulations. Also, the operation of porous pavements under snow and ice conditions should be evaluated in detail.

Instrumented porous pavement systems would be desirable. This instrumentation should provide information on rainfall, drainage, soil moisture, and water quality effects; the data provided should be continuous during the progress of a storm, thereby allowing an evaluation of dynamic changes in runoff and water quality. Toward this end, a detailed analysis is being undertaken in Phase II of this study. Phase II includes the evaluation of porous pavement and comparison to various other pavement types. The data to be collected should prove helpful in identifying the drainage and water quality benefits to be derived by porous pavements for a variety of rainfall events. Also, presently unpredictable problems may be uncovered.

The following paragraphs discuss specific recommendations in regard to future analyses that may be conducted for porous pavement systems:

1) A detailed evaluation of runoff and water quality with respect to porous pavement must be conducted. It would be desirable to determine these characteristics under various rainfall intensities and climates. At present, the only site thus observed is at The Woodlands, Texas. It would be interesting to determine if pavement infiltration rates can be exceeded by naturally occurring rainfall intensities because pavement environmental factors may affect the pavement infiltration rate. Also, factual data is required for all climates in order to prove porous pavement is truly effective world-wide. Particular attention must be paid to winter conditions - the effects of freezing, de-icing materials, and maintenance (snow removal, etc.). The Naval Civil Engineering Laboratory has surveyed five porous friction courses in Great Britain and West Germany. Although the evaluations were favorable in regard to service life in cold climates, similar efforts for comparison purposes should be undertaken in the United States, particularly in the mid-western and mountainous parts of the nation.

2) Another aspect of porous pavement evaluation is the duration of base saturation and its effect on pavement life and load bearing capacity. Because existing conventional pavements may have saturated bases for extended periods as a result of infiltration through pavement surface cracks, it seems that base and subbase saturation should not be a problem, particularly since pavement strength is based on saturated conditions. Although conventional roadway base material has a critical water content limit, in large graded base material, where load transfer is basically independent of water content, the load-bearing capacity of the base may not be substantially affected. However, the subbase may lose some strength. This loss in strength may be related to the proportion of granular materials in the subbase. It would be desirable to investigate this loss of strength characteristic for various subbase materials. Only site condition evaluation can determine the design adequacy under a non-uniform dynamic traffic loading situation. Also, if the gravel tends to become embedded in the saturated subbase during pavement loading, the efficacy of a more stable but permeable membrane (filter cloth) or sand layer must be investigated.

3) A third and conjunctive area of interest is the change in water quality as runoff moves through the surface course into the base course and finally into the subbase. These changes may also depend on the detention time in the base. If any correlation between detention time, base and subbase chemical composition, and water quality can be determined, the design of porous pavement systems for water quality would be vastly improved. As a result of rapid introduction of polluted runoff into the subbase, the effects on soil chemistry and biology as well as ground water must be considered. Anaerobic bacteria culture in the base may allow biological water treatment processes to be introduced into porous pavement systems. One major problem will be the assurance of bacteria medium survival during dry periods between storms. If this approach proves successful, the efficiency of porous pavement systems with regard to water quality control will be greatly increased.

4) The question of porous pavement surface clogging by urban dirt and sand is of concern to most users. The feasibility of pavement clogging and the efficiency of currently available equipment to restore premeability should be investigated in order to provide maximum life expectancy of the pavement. Existing data indicate that the surface of porous pavement is not easily clogged under general use, but accidental spills of cloggable material do result in reduced pavement permeabilities which can be restored with vacuum cleaning and hosing with a water jet. In extreme cases, additional drain holes may be required to be drilled in the pavement surface course.

5) Loss of cementitious properties in the asphalt or polishing of base gravel by certain pollutants in runoff, e.g., acidic rain or spilled gasoline, must be investigated. The results of this effort will provide means of identifying critical localities or undesirable pollutants for which adequate precautions must be taken. If a certain pollutant is found to be undesirable, porous pavement systems designed for

this area should be located away from runoff carrying these pollutants. Another phase of this investigation should address the feasibility of using an impermeable liner between the base and subbase. This results in storage of runoff for future treatment or disposal and consequently the effects of long-term contact with polluted runoff must be evaluated.

6) A standard set of construction specifications should be developed for open graded porous pavement mix design and construction. However, the specifications should be flexible enough to allow certain design changes if needed. Also, the design procedure and guide specifications for porous pavement as supplied in this report should be investigated and utilized whenever possible.

7) The aggregate gradation and asphalt content for the porous pavement and porous friction course mixes should be standardized so as to provide greater acceptability by the design engineer and contractor. Standardization should be on a regional or local basis because of material availability and construction methods. This approach will allow a more standard pavement structural design and will obviate the need to conduct a large series of tests for each project. Furthermore, as engineers and contractors gain experience in this type of pavement construction, and as research on the design of mixes provides for an optimum design, the cost of designing and installing porous pavement lots will probably be reduced. The development of asphalt additives, e.g., neoprene, or other binding agents to improve porous pavement service life and performance must be evaluated. As the acceptability of porous pavements increases, these new materials may become evident by exposure to different paving materials.

8) Asphalt hot mix plants should be reorganized to provide uniform stockpiles and desirable aggregate cold feed in order to assure that the aggregate will have the desired properties identified in the specifications.

9) The economy of porous pavement usage relative to conventional paving must be evaluated because this aspect will be of major concern to most owners and developers of porous pavement systems. In particular, if all aspects of porous pavement need not be considered, e.g., areas where urban runoff water quality is not of concern, then the cost comparison to conventional paving may not be as complete or as valid, especially at present when construction experience leans heavily toward conventional paving.

10) Public awareness of the porous pavement approach to runoff and water quality control must be encouraged because most people do not generally recognize any difference between porous and conventional asphalt pavements which are similar in appearance. Increased public acceptance of proven porous pavement systems will result in rapid responses to public demand by local government officials and planning and designing communities.

SECTION 4

BACKGROUND

The Federal Water Pollution Control Act Amendments of 1972 (PL 92-500) set forth the requirements to insure "fishable and swimmable water" throughout the nation by 1983 and to eliminate any polluting discharge into these waters by 1985. Section 208 of this Act provides for areawide water quality management planning which has subsequently been authorized under various sections of the Federal Clean Water Act of 1977 (PL 95-217).

The accumulation and analysis of water quality data from urban areas by various investigators (5, 6, 7) has indicated that storm water runoff is a major non-point source of pollution. Structural measures to alleviate this problem have often been the solution; however, former USEPA Administrator Russel E. Train (8) and other proponents of non-structural measures, specifically land use controls, have been recognized and appreciated in recent years. The primary objective of land use controls is not exclusion of specific uses, but rather inclusion of land use practices which do not degrade the receiving water quality. The installation of porous pavements in urban areas is one significant land use practice which can be used to meet the water quality objectives of PL 92-500.

A second set of Federal legislation which affects land uses in urban areas is Section 1302 of the National Flood Insurance Act Amendments of 1968, which encourages state and local governments to "make appropriate land use adjustments to restrict the development of land, which is exposed to flood damage..." This objective was enforced by the Flood Disaster Protection Act of 1973 (PL 93-234) by requiring states and local governments, as a condition for future Federal financial assistance, to participate in the flood insurance program and to adopt adequate flood plain ordinances with effective enforcement provisions.

The enforcement of these ordinances is contingent upon a stable hydrologic regime; however, Brater (9), Espey, Morgan and Masch (10), McPherson (11), and others have indicated increased runoff rates and peak discharges after urbanization which result in downstream land which originally experienced no flood hazard becoming flood-prone. Therefore, upstream land use practices impact upon downstream areas, and, in recognition of this fact, numerous municipalities have enacted legislation to prevent increases in runoff rates, and sometimes volumes, from development sites.

The use of porous asphalt pavement for runoff control and water quality enhancement is a relatively recent development. Open graded (large size aggregate

only and therefore porous) asphaltic mix was initially developed and tested for safety applications as friction courses on conventional paving.

Porous friction courses 3/4 to 1 inch (1.91-2.54 cm) thick are used on conventionally paved and impermeable surfaces with the objective being to remove surface water from the pavement and still maintain a dry base strong enough to sustain design traffic loads.

Porous friction courses allow drainage through the voids in the mix, and if adequate transverse grades are provided, out to the shoulders. The rapid removal of surface water results in minimum pressure build-up under moving vehicle tires and consequently, increased wet skid resistance and elimination of hydroplaning, as previously described.

The elimination of hydroplaning and the improved wet skid resistance by application of open graded asphaltic mix to conventional paving encouraged the highway departments of California, Nevada, New Mexico, Utah, and Louisiana to incorporate open graded friction courses in their highway design. The aforementioned safety features also instigated the use of porous friction courses for airport runways; initially at Farnborough, England in 1967, by the British Royal Air Force, and by the United States Air Force at two military air fields in Europe. In 1971, the United States Naval Facilities Engineering Command installed a porous friction course on the main runway at Hensley Airfield at the Naval Air Station in Dallas, Texas. Concurrently, the United States Air Force Weapons Laboratory constructed test strips of 8 different porous friction courses at Kirtland Air Force Base in Albuquerque, New Mexico (12). Subsequent applications of porous friction courses include Peace Air Force Base, New Hampshire; airports at Salt Lake City, Denver, Greensboro (North Carolina); and several more state highway departments, including Colorado, Kentucky, and Pennsylvania.

In all of these early investigations, emphasis was placed on removing surface water laterally through the asphalt bound open graded matrix. Although the rate of runoff was also affected, this aspect was not investigated. The total design for this system also required a permanently sealed and prepared base and, therefore, the runoff volume of the paved area was unchanged by addition of the open graded overlay.

On the other hand, the use of an open graded base course was first incorporated into highway design in 1947 on United States Highway 99, near Red Bluff, California. 7.1 miles (11.4 km) of this highway were constructed with a 3/4-inch (1.91 cm) conventional asphalt concrete wearing course over an open graded asphaltic concrete binder course, 2.4 inches (6.10 cm) thick, underlain by a 6-inch (15.24 cm) cement treated base and a gravel subbase. After 10 years of service under heavy truck traffic, this road was still in very good condition and has required minimum maintenance (13).

Since 1966, the United States Forest Service has been using permeable materials to repave forest roads in the Pacific Northwestern states. This pavement consists of 4 to 10 inches (10.2-25.4 cm) of crushed rock, held together with asphalt binder and a thin chip seal wearing course. Most of these roads carry large numbers of heavy logging trucks rather successfully because the water drains into the pavement and, because of the generally steep grades, water drains away from the roadway very quickly (14).

This concept of using an open graded gravel base between an existing prepared subbase and a conventional asphalt concrete or concrete wearing course has been developed and applied to several areas in California. The theory behind this concept is to rapidly remove any water that percolated into the open graded base. This removal is achieved by means of drain pipe collectors which discharge into adjacent roadside ditches. This approach is based on the idea that the best solution for pavement drainage is to install an artificial drain system under the wearing course to prevent saturation of the underlying subbase layers of soil. Water filtering through the cracks in the pavement is rapidly discharged horizontally through the gravel base so it does not stand on the subgrade long enough to saturate and weaken it. A total pavement thickness of 8 to 10 inches (20.3-25.4 cm) was found to be sufficient for highway design. A typical cross-section of an installation near Redwood City, California is shown in Fig. 1 (14). This installation was constructed in 1970.

During 1970 and 1971, the Franklin Institute Research Laboratories in Philadelphia, Pennsylvania, under contract with the USEPA, attempted to combine the porous friction course and the porous base concepts and thereby control runoff and enhance water quality. They investigated the use of an open graded asphalt mix underlain by a gravel base course and a minimally compacted subbase as a potential solution (1). The successful test results suggested a unique approach to meeting the requirements of the Federal Water Pollution Control and Flood Disaster Protection Acts. Several applications of this technology, generally referred to as porous asphalt, are now in operation mainly on the eastern coast and Gulf of Mexico regions of the United States, as listed in Table 1.

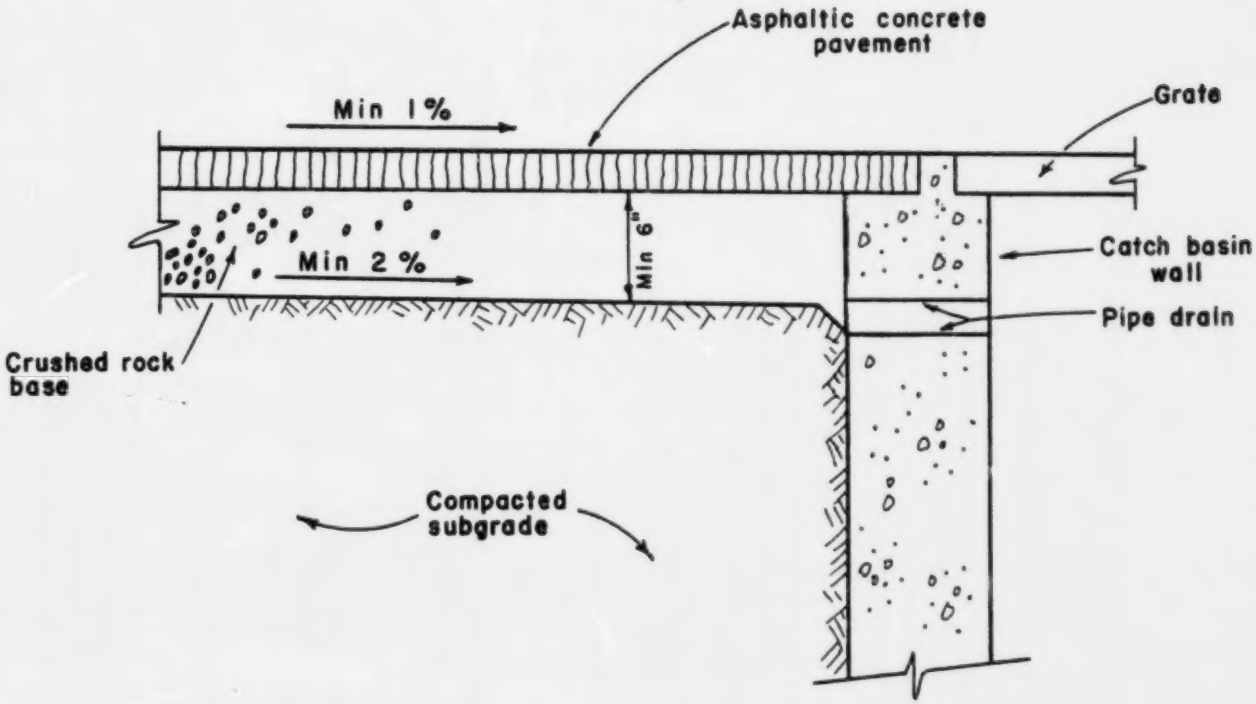


FIGURE 1

ORIGINAL OPEN GRADED BASE COURSE APPLICATION

SECTION 5

DESCRIPTION OF POROUS ASPHALT PAVEMENTS

In general, porous pavement is composed of four layers:

1. Minimally compacted subbase consisting of undisturbed existing soil or, in the case of unsuitable base soils, an imported and prepared base course. Auxiliary drainage structures (French drains, pipe drains, etc.) may also be required.

2. Reservoir base course consisting of 1 to 2 inches (2.54-5.08 cm) diameter crushed stone aggregate. The thickness of this layer is determined from runoff storage needs and frost depth considerations as described later in this report.

3. Two inches (5.08 cm) of ½-inch (1.27 cm) crushed stone aggregate to stabilize the reservoir base course surface.

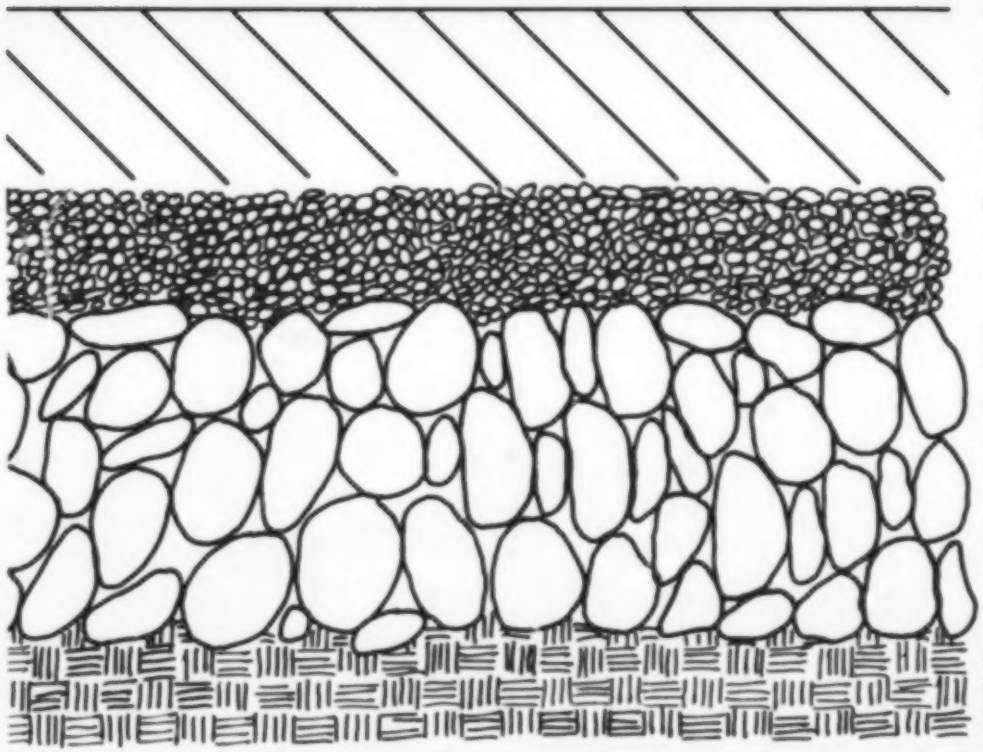
4. Porous asphalt concrete surface course whose thickness is based on bearing strength and pavement design requirements. In most applications, 2½ inches (6.35 cm) has been found to be sufficient.

A typical porous asphalt pavement cross-section is presented in Fig. 2. The following descriptions are adapted from Thelen and Howe (15).

The Subbase

All soils under roads may become wet, but they must drain in order to maintain their bearing strength. Because soils under porous pavement will get wet, they must be permeable to water; they must not heave due to freezing or thawing, and they must not swell or substantially lose their strength when wet. Most soils can meet these requirements if proper drainage is available. In current practice it is very important that the subbase under conventional pavement remain dry and that pavements often may be wet due to cracks in the pavement, percolation through the shoulders, and capillarity from ground water. However, base strength is essentially retained because free water can drain away, leaving the soil particle structure intact. Soil strengths, as defined by the California Bearing Ratio, are measured on wet soils because soil wetness is anticipated.

The contaminants on a road surface can range from random spills and pesticides to engine fuel residues. In a storm sewer or street system, they are typically collected in the initial runoff and discharged at one point in a receiving



POROUS ASPHALT COURSE
1/2" TO 3/4" AGGREGATE
ASPHALTIC MIX (1.27 - 1.91 cm.)

FILTER COURSE
1/2" CRUSHED STONE (1.27 cm)
2" THICK (5.08 cm)

RESERVOIR COURSE
(2.54 - 5.08 cm)
1" TO 2" CRUSHED STONE VOIDS
VOLUME IS DESIGNED FOR RUNOFF
DETENTION

THICKNESS IS BASED ON STORAGE
REQUIRED AND FROST PENETRA-
TION

EXISTING SOIL
MINIMAL COMPACTION TO RETAIN
POROSITY AND PERMEABILITY

FIGURE 2

POROUS ASPHALT PAVING TYPICAL SECTION

stream; in the porous pavement system they are delivered to the soil over the entire area of the pavement.

It is expected that contaminated water will tend to be purified as it passes through the soil, as a result of absorption of contaminants by soil particles, bacterial action, and dilution. On the other hand, water passing through soil may leach out minerals and pick up bacteria.

At the Franklin Institute Research Laboratories, preliminary tests indicated that aerobic bacteria can live in the soil under porous pavement; these could act like sewage treatment plants to digest organic contaminants. At The Woodlands, Texas site (4), aerobic digestion was discovered, with ammonia in the runoff being converted to nitrites and nitrates. Further reduction was not possible due to faulty drainage of the subbase. However, the nitrogen in the runoff from the control pavement was mostly nitrates. Both total organic carbon and chemical oxygen demand were much lower in the porous pavement percolate than in the runoff, because of bacterial action in the base and subbase. The limestone base material also raised the conductivity of the percolate which then neutralized the carbonic acid in the rain and runoff.

Even though initial runoff had high lead concentrations, the percolate at The Woodlands site showed practically no lead, because of faulty drainage of the subbase, so that the percolate was diluted by storage, and because lead accumulations were not significant.

The Reservoir Base Course

In conventional pavement, the base consists of stones, sand, and dust particles packed into a dense mass and designed to transmit mechanical loads from the hardtop to the soil below.

In porous pavement, the base consists of large-sized and graded stones, lightly rolled into an open, interlocking structure which not only transmits mechanical loads, but also stores runoff water which the soil cannot immediately absorb. This water is held in the reservoir formed by voids in the rock matrix until it can percolate into the soil. For size gradations recommended in this report, the voids will be as high as forty percent of the total volume. Of course, if the soil has a higher permeability rate than the rate of rainfall, a reservoir is not needed. However, this is unlikely because maximum rainfall intensities of design storms are generally much higher than the infiltration rates of most soils.

The aim of having a reservoir is to store runoff water for several hours to allow it to percolate into the soil. On sloping pavements, base areas at the higher end of the site are not credited with storage capability even though water enters the base in these areas, because they drain laterally and do not contribute to the percolation system at the higher end of the site.

Because the base reservoir serves a purpose similar to retention basins, runoff from roofs or other impervious and pervious surfaces could be drained into it; but the base must be designed to have the required capacity.

The aggregate used in the base must be hard and durable. Generally it is angular and not round. Crushed stone is the most desirable material because the aggregate interlocks very well. Rounded gravel must be avoided for all areas where heavy traffic is anticipated. The crushed stone should come from one of the following rock groups:

(a) Granite

(b) Basalt

(c) Gabbro

(d) Porphyry

(e) Blast furnace slag

Limestones which are susceptible to polishing by water should be used in only special situations where design loads are within the loading limits for this type of material.

The Reservoir Top Stabilizing Course

To assist in final grading of the reservoir base course to stabilize the surface, a two-inch (5.08 cm) layer of ½-inch (1.91 cm) crushed stone aggregate is recommended. Based on previous construction experience, this stabilizer course is necessary because construction vehicles hauling the asphalt hot mix across the reservoir course would create ruts which consequently require constant regrading to finished grade immediately prior to application of the hot mix.

Open Graded Asphalt Concrete Surface Course

Porous asphalt consists of a wearing course of open graded asphalt concrete laid over a base course of uniformly sized aggregate. It differs from conventional asphalt concrete chiefly in that it contains very little dust or sand; its void volume typically is around 16 percent, as compared with the two to three percent void volume of conventional asphalt concrete.

Asphalts used in asphalt concrete range from 50 to 100 penetration grade, depending upon the ambient temperatures and viscosity characteristics desired. In general, the grades used in a given locality for conventional asphalt concretes will suffice for porous asphalt as well. However, the porous product is more subject to scuffing, such as occurs when the front wheels of stationary cars with power

steering are turned. It is therefore suggested by Franklin Institute Research Laboratories that for porous asphalt, 50 to 60 penetration grade be used in the South (Texas, Florida, etc.), 65 to 80 in the mid-Atlantic states, and 85 to 100 penetration grade in the northern states.

The percent of asphalt should be specified between 5.5 and 6, based on the total weight of the pavement. The lower limit is to assure adequately thick layers of asphalt around the stones and the upper limit is to prevent the mix from draining asphalt during transport, particularly if it is accidentally shipped at a temperature of over 300° Fahrenheit (149° C).

To avoid damage due to photo-oxidative degradation of the asphalt (since air and sunlight can penetrate further), the asphalt coatings on the aggregate surfaces should be thicker than usual. In this case, the asphalt can form skins or otherwise be mildly degraded without significant loss of cementitiousness.

The open graded asphalt concrete is similar in Marshall properties (strength and flow) to conventional asphalt concrete. Hence, the usual thickness of base course and paving should satisfy load requirements. The base course thickness may have to be increased to provide greater reservoir capacity where runoff volumes and/or soil percolation require it.

SECTION 6

ADVANTAGES AND DISADVANTAGES OF POROUS ASPHALT PAVEMENT USAGE

The primary design objective of porous asphalt pavements is to control runoff rate and volume increases and water quality degradation resulting from developed and impervious areas in deference to the requirements of the Water Pollution Control and the Flood Disaster Protection Acts. However, numerous other primary and secondary benefits are also realized with porous asphalt pavements. Each of these benefits is identified and discussed in this section but the intensity of each benefit is a site- and region-specific function and therefore a relative evaluation was not attempted.

The advantages and/or benefits one may reasonably expect from porous asphalt pavements are as follows:

1) Runoff rate and volume control in areas where pervious ground is replaced with impervious cover. The main impact is a substantial reduction of runoff rate and volume from impervious areas. If the pavement and reservoir base are designed adequately, all of the runoff may be detained and released at a rate adequate to prevent increases in flood flows. Concurrently, the stored water may be allowed to infiltrate into the natural ground.

2) Erosion control on unprotected overland flow and channel areas. Because impervious areas generate higher rates of runoff than pervious areas, the erosive capacity of the flow is also increased by means of increased depth of flow and increased velocities. Consequently, overland flow and channel areas downstream from impervious areas would experience additional erosion and sediment removal. However, the use of porous asphalt pavement systems would reduce or entirely remove the excess runoff problem and therefore considerable benefits may be derived from bank and soil protection and sediment reduction.

3) Water quality enhancement will be evident in areas where the runoff generated from impervious areas has the potential for becoming contaminated, as in the case of industrial and commercial land use areas. If the pollution is not toxic and depending upon its characteristics, detention in the reservoir layer and percolation through the subbase may be sufficient to reduce the pollution to acceptable levels.

If the stormwater requires treatment for toxic or non-filterable substances, it may be stored in porous pavement systems isolated from the natural ground by an impermeable membrane until treatment plant capacity becomes available. Thus,

treatment plant capacity does not need to be expanded. Also, detention of highly polluted initial runoff by the porous pavement, and dilution by less polluted subsequent runoff can result in acceptable pollution concentrations throughout the storm duration.

4) The need for curbs and storm sewer installation or expansion may be avoided. In already urbanized areas, such as established areas of most cities as well as existing shopping centers, where the storm sewer network was designed and installed prior to excessive impervious cover development (parking lot expansion, etc.), the storm sewers may become overloaded, and if parking lot or roof storage is not a design criterion, the disposal of excess runoff becomes a problem that porous pavements could solve. This benefit is enhanced in areas with combined sewerage because the probability of sewer overloading and the resultant discharge of raw sewage into the receiving water is reduced.

In areas of slight topography or with minimal soil depths, the cost of installing storm sewers is very high because both sewer size and excavation volumes are high. The use of porous pavements in these areas reduces both sewer size and excavation depth, thus resulting in a net savings in drainage costs.

5) Natural drainage boundaries and patterns can be maintained. Consequently, elaborate drainage schemes to collect and deliver runoff to a safe conveyance will not be necessary. Instead, drainage boundaries existing prior to development may be retained without sacrificing the finished grade of the paving.

6) The nuisance factor to pedestrian and motorist arising from standing puddles in parking lots, streets, and detention basins will not be a problem. Also, disease vector control (mosquitoes, etc.) may be accomplished through the use of porous pavement systems.

7) Natural vegetation and drainage patterns can be retained by the use of porous pavements. Consequently, the clearing of trees from large areas for parking lots is unnecessary and secondary aesthetic benefits are also derived. This also applies to roadside vegetation in highly developed areas where, under conventional paving, the soil moisture is severely deficient.

8) Groundwater recharge may be possible with porous asphalt paving. In water deficient areas, impermeable paving may prevent recharge to a local aquifer and thereby reduce its safe yield. Porous paving would correct this condition.

9) The full range of safety improvements resulting from porous pavements has been evaluated only at The Woodlands, Texas, site (4). However, as previously discussed, the improvements to wet pavement skid resistance have been used successfully on road surfaces in numerous states and airport pavements in England, New Mexico and New Hampshire. The results of sliding friction tests

conducted by Hollinger (4) at The Woodlands site and the United States Air Force Weapons Laboratory at the Dallas site (12) are presented in Table 4. As expected, the friction coefficients for wet porous paving are significantly greater than for wet conventional paving. Also during these tests a singular, and as yet unresolved, anomaly was discovered at The Woodlands site - porous pavement surfaces have a higher friction coefficient when wet than when they are dry. Hollinger also determined that:

a) Porous asphalt pavements generate slightly less traffic noise than conventional asphalt pavements.

b) There is no real difference in light intensity reflected from white and yellow markings on either type of pavement. However, the effects of glare from oncoming vehicle lights, which obscure the reflected light from paint on a wet conventional asphalt pavement, were not evaluated.

c) Porous asphalt pavements tend to deflect for a longer time than conventional asphalt pavements, but the magnitude of deflection is approximately equal.

On the negative side of porous pavement usage, the most often expressed concern is the susceptibility of the pavement to clogging. With proper care and maintenance, this problem should not occur and past experience supports the veracity of this statement.

Clogging of the pavement pores generally occurs due to operational and construction scheduling problems. For example, spills of construction materials on finished pavements, or hillside erosion and sedimentation on finished pavements may clog the pavement or reduce its permeability. Obviously, the solution to construction-related problems with porous pavements is to finish all ground preparation and earth work prior to installation of porous pavements. After construction, the haulage of clogable materials across porous pavements must be conducted with extreme care to prevent spills.

If a spill should occur, immediate vacuuming and washing with a water jet will restore pavement permeability almost to pre-spill rates - tests conducted at The Woodlands site indicate a permeability recovery in excess of 95 percent. However, if the pores are clogged and the dirt is compacted or ground in by traffic to a depth greater than 0.5 inches (1.27 cm), full permeability cannot be restored. In this case, holes may be drilled through the clogged area to provide the necessary drainage. The areal distribution of holes required would be a function of pavement slope and degree of clogging.

Porous pavement surfaces can also be ineffective during the melting of snow which has accumulated on the surface; or if rain occurs on a frozen surface.

TABLE 4

FRICTION COEFFICIENTS FOR POROUS PAVEMENT SURFACES

TEST DATE	PAVEMENT TYPE	DRY CONDITION	WET CONDITION
	Dallas, Texas (12)		
11/71	Porous asphalt	0.76	0.70
	Conventional asphalt	0.74	0.16
	Grooved concrete	0.76	0.71
	Woodlands, Texas (4)		
12/75	Porous Asphalt old	0.61	0.85
	Porous asphalt new	0.66	0.74
	Conventional asphalt	0.73	0.59
2/76	Porous asphalt old	0.82	0.95
	Porous asphalt new	0.83	0.90
	Conventional asphalt	0.99	0.81
4/76	Porous asphalt old	0.74	0.84
	Porous asphalt new	0.80	0.84
	Conventional asphalt	0.78	0.71

A second disadvantage in the use of porous pavement results from the fact that some existing building codes and regulations are not intended for this new type of technology. Specifically, if conventional drainage structures (curbs, gutters, inlets, etc.) are arbitrarily required in all parking areas, then the construction costs of porous pavement installation become economically excessive.

A temporary drawback arises out of a lack of data to indicate the capabilities of porous pavement to filter and purify all contaminants in runoff. Initial results at The Woodlands site indicate a reduction of most pollutants, but the data is insufficient for generalization. Also, it is obvious that severely polluted runoff should be excluded from a porous pavement because of its susceptibility to clogging.

Spillage of gasoline from leaking tanks of automobiles parked on the porous pavement lot will break down the asphalt binder to greater depths than on conventional pavements, primarily because the pores on the open graded mix permit excursion of the gasoline into a larger spatial volume. The solution to this problem may be the use of tar binders rather than asphalt.

The negative aspects of porous pavements as discussed above are not insurmountable in most instances. Also, the advantages far outweigh the disadvantages. Consequently, the potential for porous pavement usage is expected to increase as the problems outlined in this section are resolved.

SECTION 7

DESIGN CONSIDERATIONS

The design of a porous pavement parking area requires the same basic procedures as for a conventional parking area. However, the drainage aspects and the corresponding changes in load-bearing capacity of the pavement require detailed attention. In general, the design procedure will follow 3 basic functions:

1. Determination of existing soil properties
2. Load-bearing design of pavement and subgrade
3. Hydrologic design of pavement and subgrade

In addition to these 3 basic functions, corresponding operational and maintenance factors during and after construction must also be considered. Each of the functions is described in the following discussion:

Determination of Existing Soil Properties

At most building sites, the location of the parking area is governed by numerous factors, including;

a. Building aspects
b. Aesthetics
c. Convenience
d. Surface slope

During the pre-design phase, factors affecting porous pavement installation must also be considered.

Initially, a site inspection is imperative. Environmentally critical, unique, and undevelopable areas must be identified and adequate precautions taken to prevent damage to these areas during and after construction. The ideal location for porous pavement is a well-drained soil on a relatively flat slope. Desirable trees and shrubs which will not significantly affect traffic patterns and yet provide shade and beauty to the area must also be identified and demarcated for preservation. Predominantly clay soils must be avoided or, if this is not possible, relief measures must be adopted in the design.

All available soil data for the site should be acquired and inspected. The United States Department of Agriculture Soil Conservation Service has developed soil maps for most counties in the United States; but in some areas even more detailed soil information may be available. The Soil Conservation Service has classified most soils into 4 hydrologic soil groups, defined as follows:

(A) Soils having high infiltration rates, when thoroughly saturated and consisting chiefly of deep and well-drained sand or gravel. These soils have a high rate of water transmission and low runoff potential.

(B) Soils having moderate infiltration rates, when thoroughly saturated and consisting chiefly of generally deep and well-drained soils with moderately fine to moderately coarse texture. These soils have a moderate rate of water transmission.

(C) Soils having slow infiltration rates when thoroughly saturated and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine or fine texture. These soils have a low rate of water transmission.

(D) Soils having a very slow infiltration rate when thoroughly saturated and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission and a very high runoff potential.

In the above definitions, infiltration rate is the rate at which water enters the soil at the surface, which is controlled by surface conditions (percolation rate), and the transmission rate is the rate at which the water moves in the soil and is controlled by the soil horizons or layers.

Appendix B presents a list of more than 4,000 soils in the United States and Puerto Rico compiled by the Soil Conservation Service with hydrologic soil group classifications for each soil. These classifications are based partly on the use of rainfall runoff data from small watersheds or infiltrometer plots. However, the majority of the classifications are based on the judgement of soil scientists who use physical properties of the soil in making their decisions. Each soil was classified in a particular hydrologic group by comparing its profile with profiles of soils already classified. It was assumed that the soil surfaces were bare, maximum swelling had taken place, and rainfall rates exceeded surface detention and infiltration. Thus, most of the classifications are based on the premise that similar soils (similar in depth, organic matter content, structure, and degree of swelling when saturated)

will respond in an essentially similar manner during a rainstorm having sufficient intensities to generate runoff.

If the site inspection or other information indicates that the original soil classification may not be correct, additional testing may be required to properly identify the hydrologic soil group for that particular soil. Hydrologic soil groups (A) and (B) are ideal for porous paving sites. However, potential areas in soil groups (C) and (D) require more attention. In certain areas (low design runoff volumes), soil groups (C) and (D) may be acceptable. However, in the general case, appropriate external drainage measures, e.g., greater excavation and replacement with porous or drainable fill, may be justified.

After the site is tentatively located for the best available location and drainage conditions, core samples must be taken of the soils which will lie under the proposed parking area. Core depth should go down to the water table or impermeable layer of rock or clay. If this is impractical, borings should extend to a depth sufficient to indicate no barriers to vertical seepage of water. In most cases, a maximum depth of 20 feet (6.1 m) should be adequate, or if the water table is intersected prior to this, down to the water table. The soil borings must be inspected for any soil layers of reduced permeability. If bedding planes are horizontal, the permeability in the least permeable soil must be used as the soil design permeability.

If the soil structure shown by adjacent soil borings is not similar, steeply sloping or vertical, bedding plants, or previously disturbed soil (compacted fill, etc.) may be indicated. In this case, an intensive soil boring program may be necessary to assure no impermeable lenses or layers. In general, two cores may be all that is required on small parking areas no greater than ½-acre (0.2 hectare) in extent. On larger areas, the cores may be taken 100 to 150 feet (30.5 to 45.7 m) apart. However, prior experience and knowledge of the site (from foundation core analysis, etc.) may dictate a less extensive program.

The core samples are used to determine soil structures and subsurface characteristics including permeability and barriers to the movement of ground water. If surface sealing, from silt accumulation or compaction by traffic, is suspected, percolation tests may be required. These tests essentially define the surface absorption capacity and permeability of the top layer of soil. However, as mentioned previously, the least permeable layer of soil must be used to determine the design permeability of the soil mass.

Soil core samples must also be tested for bearing and shear strength. All strength and drainage tests must be conducted for dry (general) and saturated (critical) conditions. Also, susceptibility to frost heave and loss of strength under saturated conditions must also be determined.

Load Bearing Design of Pavement and Subgrade

Final design of a porous pavement system requires the determination of the total thickness of the porous pavement from top of pavement to subbase soil. This thickness is influenced by the bearing strength, water storage required, and frost depth. The greatest thickness determined by each of these conditions will be the design thickness.

Bearing strength properties of different soils have been thoroughly investigated by Franklin Institute Research Laboratories. Using the California Bearing Ratio (CBR) test, all soils can be classified into four soil strength categories, as listed in Table 5. The design traffic intensity may be divided into 3 groups, defined by the average daily Equivalent Axle Load (EAL) and the minimum thickness for each strength category and traffic intensity group defined. These results are presented in Table 6.

As described previously, the total thickness of the paving system is a combination of the open graded base course and the surface layer of open graded asphalt mix.

Recent studies by the Federal Highway Administration (FHWA) indicated that variations in asphalt content have little effect on Marshall and Hveem stabilities or flow values. However, the importance of having at least some fine aggregate to provide a "chocking" action for the stabilization of the porous aggregate fraction must be recognized. Also, a minimum of 2 percent passing the Number 200 sieve must be required to control the asphalt drainage characteristics of the mixture by effectively increasing the viscosity of asphalt cement.

The Franklin Institute Research Laboratory and the FHWA recommended gradation limits for aggregate mix as well as gradation limits developed by the U.S. Army Corps of Engineers' Waterways Experiment Station (WES) and U.S. Naval Facilities Engineering Command (NAVFAC) and others are listed in Table 7 along with the slightly modified gradation limits proposed in this report. It can be seen from the comparison of gradations in Table 7 that the Franklin Institute Research Laboratories gradation allows slightly larger aggregate and more fines passing the Number 8 sieve. However, it does not require any mineral filler passing the Number 200 sieve or fines passing the Number 16 sieve. The gradation recommendation herein is essentially similar to that recommended by the Franklin Institute Research Laboratories, except that a minimum of two percent passing the Number 200 sieve has been included.

The reasons for favoring the Franklin Institute Research Laboratories gradations are as follows:

1. The experience with existing porous asphalt parking lots has been generally good.

TABLE 5

SOIL STRENGTH CATEGORIES

Soil Description	Strength - CBR
1. EXCELLENT Containing a uniformly high percentage of granular materials Unified Soil Classes: GW, GM, GC, GP; some SM, SP, and SC AASHO Soil Groups: A-1, A-2, some A-3's	15 - plus
2. GOOD Containing some granular materials intermixed with silt and/or light clay Unified Soil Classes: SM, SP, SC; some ML, CL, CH AASHO Soil Groups: A-2, A-3, some A-4's a few A-6's or A-7's	10 - 14
3. FAIR Sand clays, sandy silts, or light silty clays if lot in in mica content; may have some plasticity Unified Soil Classes: ML, CL; some MH, CH AASHO Soil Groups: Ranging from A-4 to A-7 (Low Group Indices)	6 - 9
4. POOR Plastic clays, fine silts, very fine or micaceous silty clays Unified Soil Classes: MH, CH, OL, OH (Pt unsuitable) AASHO Soil Groups: Ranging from A-4 to A-7 (Higher Group Indicies)	5 or less

TABLE 6

MINIMUM THICKNESS OF POROUS PAVING FOR VARIOUS LOADING CONDITIONS

Traffic Group	General Character	CBR 15 - plus	CBR 10 -	CBR 6 - 9	CBR 5 - less*	EAL
1	Light Traffic	5"	7"	9"		5 - less
2	Medium Light (Max. 1000 VPD)	6"	8"	11"		6 - 20
3	Medium (Max. 3000 VPD)	7"	9"	12"		21 - 75

* Studies indicated that for all traffic areas (1,2,3) with a CBR of 5 or less, the subgrade was improved to 6CBR with crushed stone 2" size

VPD = vehicles per day
EAL = equivalent axle load (18 Kips) average daily

Note: 1 inch = 2.54 cm

TABLE 7

AGGREGATE GRADATION LIMITS FOR POROUS ASPHALT MIXES

Sieve Size	Percent Passing			
	Gradation Recommended	FHWA	Franklin Institute	
1/2"	100		100	
3/8"	90 - 100	100	90 - 100	
#4	35 - 50	30 - 50	35 - 50	
#8	15 - 32	5 - 15	15 - 32	
#16	2 - 15		0 - 15	
#200	2 - 15	2 - 5	0 - 3	
	Newark, Delaware	Chester Co., Pennsylvania	Greensboro, N. Carolina	Dallas, Texas
1/2"	100	100	100	100
3/8"	90 - 100	95 - 100	97	90 - 100
#4	35 - 50	35	38	30 - 55
#8	15 - 32	15	15.7	0 - 22
#16	0 - 15	10	6.1	0 - 12
#200	0 - 3	2	2.0	0 - 5
	Perth Australia			
13.2 mm	100			
9.5 mm	96			
6.7 mm	66			
4.75 mm	38			
2.36 mm	22			
1.18 mm	15			
0.6 mm	13			
0.3 mm	13			
0.15 mm	5			
0.075 mm	3			

Note: 1 inch = 2.54 cm

2. The FHWS, WES, and NAVFAC mixes are aimed at a thin overlay over existing pavements, whereas the Franklin Institute Research Laboratories mix has been placed in a thicker layer over open graded base material.

3. The primary objective of the FHWA open graded asphalt friction course is removal of water from the surface of the pavement. The objective of the Franklin Institute Research Laboratories porous asphalt pavement, however, is to provide a porous and stable surface over base material that essentially functions as a water storage basin.

4. The traffic levels experienced by existing pavements using each type of gradation have been different, although the Franklin Institute gradation originated from California experience on highways.

The approach to mix design taken from FHWA is aimed at testing the porous aggregate to arrive at the surface coverage capacity, which includes absorption, superficial area, and surface roughness. All of these properties affect the asphalt cement requirement. A simple linear relationship obtained from field experience is then applied to arrive at the percent asphalt that should both provide the necessary cementation between particles and leave sufficient voids (the average FHWA goal is a minimum of 15 percent voids as compared to Franklin Institute Research Laboratories goal of 16 percent) while not creating excess asphalt that will drain or cause flushing.

The relatively open spaces within a porous asphalt mix require that additional resistance to oxidation, raveling, and retention of cementitious properties is required of the asphalt binder. Consequently, the aggregate particle must be coated with asphalt films in the range of 3 to 4 times those of conventional asphalt concrete. The asphalt content used in porous friction courses has generally been approximately 6.5 percent by weight. Initially, this content was selected to minimize the probability of excess drainage asphalt. Also, the mixing temperature was selected to be relatively higher than the temperature used for conventional asphalt mixes. Table 8 lists the asphalt content recommended and used by various agencies.

The Franklin Institute Research Laboratories mix design goals are similar to those for a porous friction asphalt course, but the approach has been one of simply applying a narrow band of asphalt content of 5.5 to 6 percent which has proven effective for the aggregates tested.

In a recent innovation by Husky Oil Company, the tenacity, ductility, toughness, and low and high temperature performance of asphalt has been significantly enhanced by the addition of neoprene. This modified asphalt contains

TABLE 8

RECOMMENDED ASPHALT CONTENT FOR
POROUS ASPHALT MIXES

Location	Thickness Inches	Asphalt Content %	Temperature °F
Newark, Delaware	2.5	5.5	275 - 300
New Castle Co., Delaware	2.5	6.0	275
Chester Co., Pennsylvania	2.5	5.0	240 - 280
Newtown, Pennsylvania	4.0	5.0	
Perth, Australia	2.0	5.0	212 - 257
Woodlands, Texas	2.5	6.0	300
Greensboro, N. Carolina	0.75	6.5	280
Dallas, Texas	0.63	6.5	240

Note: 1 inch = 2.54 cm
$^{o}F = 1.8(^{o}C) + 32$

1.5 percent neoprene synthetic rubber which was specially formulated by the DuPont Company for asphalt applications, and was used as a binder for the porous friction courses at the Salt Lake City, Utah International Airport and Stapleton International Airport in Denver, Colorado. It has been shown that neoprene has good aging characteristics with high resistance to deterioration from ozone, sunlight, heat, and weathering (16).

This product was tested at varying temperatures and asphalt content in a porous friction course mix for the Greenboro-High Point-Winston-Salem Regional Airport. The variations investigated and the resulting asphalt mix performance are indicated in Table 9. Based on these results, the optimum asphalt binder content was selected to be 6.5 percent and a mixing temperature of 300° F (149° C) at a viscosity of 275 centistokes (16).

When design construction actually proceeds on a specific porous asphalt pavement, it is suggested that asphalt drainage tests such as those described by FHWA be conducted on the recommended mix to establish the sufficiency of 5.5 to 6 percent asphalt content for the specific aggregate characteristics that will be proposed for use. This approach will be much more direct than implementing the detailed tests recommended by the FHWA for their open graded asphalt friction course. It will also provide a more positive approach than the general assumption that a single asphalt cement content is sufficient for all aggregates.

Some other considerations in the preparation of the open graded asphalt concrete mix are as follows:

1. Relatively dry aggregates should be used to avoid vapor release after the aggregate is coated.

2. Problems of crusting on the surface of the truck load during haul may be experienced; consequently, the use of insulated covers over the load to avoid heat loss is recommended.

3. Most types of compaction equipment have been used successfully, but medium to light weight vibratory rollers are somewhat better. Also, the pavement has to be sufficiently cooled before rolling in order to retain its shape.

4. The vibrating screed on laydown equipment is probably better for this application than the tamping screed.

5. Damage from freeze thaw on this kind of pavement is minimal.

At present, this type of pavement system is almost completely outside the experience of most pavement engineers and pavement contractors. Because the classical need for high density and low air voids in conventional pavement is the

TABLE 9

EFFECTS OF VARYING ASPHALT CONTENT AND MIXING TEMPERATURES ON POROUS PAVEMENT MIXES (16)

Asphalt Content %	Mixing Temperature Deg. F	Comments
6.5	280	Satisfactory
6.5	300	Smoother laydown
6.5	320	Bleeding in laydown machine hopper
6.5	300	Satisfactory
6.75	300	Satisfactory
7.0	300	Loss of mix consistency, individual aggregate could be separated from mix

Note: $^{o}F = 1.8(^{o}C) + 32$

direct opposite of the construction goal for porous pavement systems, previous experience of both design and construction personnel is to some extent obviated.

The porous asphalt cement layer is recommended to be 2½ inches (6.35 cm) in depth and the mix is to consist of the gradation previously recommended with 5.5 to 6.0 percent asphalt content initially. In order to obtain this close limit on asphalt content, it is proposed to specify 5.75 percent and to establish a tolerance of 0.25 percent on asphalt. Because the usual tolerance is approximately 0.5 percent, it is not certain that this low tolerance can be obtained; however, it is believed that it will be more nearly accepted if this type of tolerance is exercised in the specifications.

Compaction with light equipment must be applied on a closely observed basis to avoid over-compaction and collapsing of pores during construction. This should be carefully organized at the time of construction. Sample specifications presented in Appendix A have been developed by combining features of tentative specifications developed by Franklin Institute Research Laboratories and the Texas Transportation Institute.

Hydrologic Design of Pavement and Subgrade

The thickness for porous pavement systems required for the storage of water may be determined from a dynamic mass balance of inflow to and outflow from the porous pavement system. As described in Section 8, a computer model, PORPAV (17), has been developed by the USEPA to perform these calculations. However, manual calculations are also feasible but very tedious. An oversimplification, in general use, substitutes a steady-state operation for the dynamic process of inflow, storage, and outflow from the porous pavement system. Furthermore, some of the earlier designs ignored soil permeability and determined the total thickness of the porous pavement system to store all runoff from the design storm. This last approach is too conservative, and not recommended for use at this time.

A very important consideration is the relative permeability of the base to the subbase under the porous pavement. If the initial undisturbed permeability of the subbase can be maintained during construction, then this permeability may be expected to be available during operation of the porous pavement system. However, if the subbase is compacted in any way, by design or inadvertently, a substantial loss in permeability may be expected. Some studies have indicated that even sand can be compacted to where its permeability is comparable to that of clay (14). Consequently, potential porous pavement areas must be treated with due care prior to and during construction to minimize subbase compaction at the site. Traffic or material storage activities on the site should also be excluded.

The design for frost depth must consider both loss of strength due to freeze thaw cycling and frost penetration, particularly in soils where more than 3 percent of the particles are smaller than 0.02 mm in diameter. Table 10 lists the Franklin

TABLE 10

POROUS PAVEMENT DESIGN THICKNESS FOR FROST DEPTH

Level	Soil Groups	Traffic Groups 1	2	3
A	Gravelly Soils	9"	10"	12"
B	Silty gravel, sandy clays	10"	12"	14"
C	Clays, gravels, plastic sand clays, silts, silty sand, silt clay	Improve subgrade with crushed stone 2" size to level "C" and to the full frost depth		

Note: 1 inch = 2.54 cm

Institute Research Laboratories recommendations for frost depth design thickness for the 3 traffic groups previously described. The local frost penetration depth at the proposed site must also be considered. This information is generally available in the building codes of most municipalities and used primarily in foundation design.

The design storm, contributing areas, and soil permeability selected for a given porous pavement design will determine the storage volume required in the base. The selection of the design storm is in most cases dictated by local drainage regulations, but more frequent (less intense) design storms may be selected if adequate handling of runoff from storms in excess of the design storm is considered. If the design storm is not specified by local regulation, a prudent choice must be made after evaluating the consequences of flooding induced or exacerbated by the proposed development. Areally large developments tend to create major flooding problems during infrequent storms, but small developments do not generally impact the existing drainage systems and more frequent storms may be selected for these areas.

The contributing area to a porous pavement system may be dictated by the design storm and local hydrologic conditions. In areas of long duration and intense rainfall, the contributing area will be minimum. However, in more arid areas, where rainfall is of short duration, the contributing area can be quite extensive. Another factor to be considered is the nature of the contributing area, because pervious and/or grassed uphill areas will not contribute as much runoff as impervious areas. In practice, most contributing areas are rooftops, driveways, and other impervious ground cover. Therefore, the design storm magnitude is generally the most important criterion for hydrologic determination of porous pavement depth.

If the design storm and contributing area are pre-defined for a given drainage area, and if the base storage capacity is physically or economically limited, drainage relief measures may be incorporated into the system. These relief measures can range from french drains and perforated pipe drains to underground cisterns. However, the drain discharge must be properly disposed of, to the most convenient drainageway, if only peak reduction of runoff is desired, or to a retention pond if both peak and volume reduction are desired.

When the subbase permeability is relatively low (hydrologic soil group (C) or (D)), a very thick base may be required to store the water, and residence time in the base may be sufficiently long to develop undesirable side effects, like freezing or anaerobic or septic water conditions. One solution would be to provide a relief drain as described above, or, as in the case of The Woodlands, Texas site, a portion of the subbase may be replaced with sand and drains located in the sand. On the other hand, if a drainage channel is available nearby, a buried trench filled with the same type base material as the porous pavement may be installed from the base reservoir side to the channel, thereby providing an underground connection and flow conduit.

When the site is level, the rain falling at a given spot stays in the reservoir until it can percolate into the ground. However, when the site is sloped, the water in the reservoir tends to flow to the lower areas, leaving the upper parts of the reservoir empty and useless. Thus, the low parts of the base should be thicker, to hold more water, and the higher parts not thicker than necessary to handle the mechanical loads.

The proposed slope of the porous pavement should be reduced as much as possible in order to utilize the base storage volume more efficiently. On any sloping porous pavement or on a horizontal porous pavement with an artificially induced hydraulic head at one end, e.g., inflow at one end only, a substantial flow may be expected through the relatively open base course, and in the case of certain pavements water may drain out of the pavement at the low end because lateral movement is much faster than infiltration. This condition could be avoided by reducing the slope, increasing the depth of the base course in the downstream direction, and installing relief drains as previously described, or terracing the area using cut-off walls under the pavement and concrete curbs on top of it. The latter option is particularly effective on very steep slopes or very large areas where site leveling would not be practical or economical.

Porous pavement, layed out on an existing low or moderate slope with adequate base storage capacity, is the most ideal, aesthetic, and economical solution because grading a site to be level can be very expensive. Also, the exposed slopes draining onto the porous pavement must be stabilized to prevent eroded materials from washing onto the pavement and clogging the pores.

Operation and Maintenance During and After Construction Activities

In general, operation and maintenance during and after construction of porous pavements is minimal and most existing sites remain functional as designed. However, one loss of porosity failure has been experienced at Bryn Mawr Hospital near Philadelphia, Pennsylvania. The reason for this failure is discussed below. Other failures could result from poor construction supervision, or lack of experience with this product.

Experience with porous friction courses has indicated several other potential problem areas. These include "cool down" time to allow the asphalt binder to set prior to the regular operations on new construction. This problem was recognized at the North Carolina Airport (16). Another problem can be the use of these porous friction courses on steep (by Interstate Highway standards) grades, where heavy trucks are required to brake. In this instance, the pores collapse and the gravel aggregate may even come apart, resulting in a loss of pavement.

The porous asphalt will lose its porosity as a result of several factors, the most important of which are listed below:

1. Eroded soil and detritus being washed onto the pavement.

2. Construction materials being deposited or tracked in by construction equipment.

3. Washing of construction equipment, especially concrete trucks, onto the pavement.

4. Finishing of concrete structures on, or adjacent to, the pavement.

5. Collapsed pores due to constant vehicle braking at the same spot (entrance, exit, curves, etc.).

6. Collapsed pores resulting from rolling of hot open graded mix before it is sufficiently cooled to resist the roller. Also, the temperature of the hot mix at the site should not be so high that the asphalt will drain away, thereby causing a loss of cementiousness.

It is obvious that with careful attention to construction scheduling, and close supervision of site operations, as well as a regular maintenance program, all of these problem areas can be avoided. Also, if a spill should occur, immediate corrective measures should be taken. Vacuuming and jet spray washing will generally restore the original pavement permeability.

Also, the use of curbs should be avoided because these can prevent wind removal of site-generated or airborne influx materials (trash and leaves) common to most parking lots. This factor is the major reason for the failure of the Bryn Mawr lot.

Furthermore, Franklin Institute Research Laboratories have determined that at some locations interficial surface tension of water on asphalt will cause the pavement to temporarily become unable to absorb water. However, after the pavement is thoroughly wet, full permeability will be restored.

In order to prevent any loss of permeability during the life cycle of the parking lot, a regular maintenance program which includes vacuuming and jet spray washing should be implemented. If substantial amounts of wind-borne materials are expected to accumulate on the pavement surface and be washed into the base by runoff, additional storage should be provided within the base for these materials. The volume required for this type of storage must be determined from site conditions and expected environmental conditions.

The greatest hazard to loss of porosity in porous pavement occurs during the construction phase. During that time, an extensive portion of the area is not protected from erosion and/or construction equipment. Therefore, special pre-

cautions must be taken to prevent construction equipment from depositing or tracking dirt onto the pavement, and to prevent sediment from adjacent hillsides being washed onto the pavement. If this should occur, immediate vacuuming and jet spray washing should be conducted.

To prevent sediment from being deposited on the pavement, sediment trap fences or diversion ditches may be installed around the pavement area. The sediment fence could be filter material or fabric anchored in the ground and supported by vertical stakes adequately spaced behind the fabric to support the water pressure. A diversion ditch should be designed to have sufficient capacity to remove all of the expected runoff and be able to maintain its grade below that of the pavement. Also, the design velocity should not exceed the non-erodible velocity for the channel lining material.

If at all possible, the installation of the porous pavement lot should be delayed to be the last construction activity on the site. This approach would necessarily involve additional soil erosion areas during construction and these would require further controls. However, the integrity of the porous pavement would be retained at a much less diligent effort. Also, some protection may be necessary immediately after construction. Once vegetation is established and most areas are stabilized, the runoff should be devoid of excess sediment material.

SECTION 8

COMPUTER MODEL FOR HYDROLOGIC DESIGN

The model developed in this project provides a comprehensive analysis of flow and storage in porous pavements. Although the model is not very complex, limited tests indicate that it can adequately quantify the hydrologic responses of a porous pavement. Also, the effects of different pavement characteristics can be evaluated. This allows for the investigation of various porous pavement systems to determine the optimum system, particularly during planning phases of a project.

The hydrologic responses of a porous pavement may be simulated by a system of hydraulically connected control volumes for which the inflows and outflows are mathematically defined. The porous pavement, the base and the natural ground (or the drain system) are considered to be sequential but internally independent storage reservoirs.

The basic equation of continuity of conservation of mass is applied to each reservoir:

$$\frac{ds}{dt} = I - O$$

where

I = inflow into the reservoir

O = outflow from the reservoir

$\frac{ds}{dt}$ = change in storage volume

Inflows to the Porous Pavement System

As shown in Fig. 3, the porous pavement area would serve to control runoff from contributing impervious areas. Therefore, inflow to the porous pavement system, RUNOFF, is defined as:

$$RUNOFF = PAV + HYD$$

where:

PAV = direct rainfall onto the porous pavement

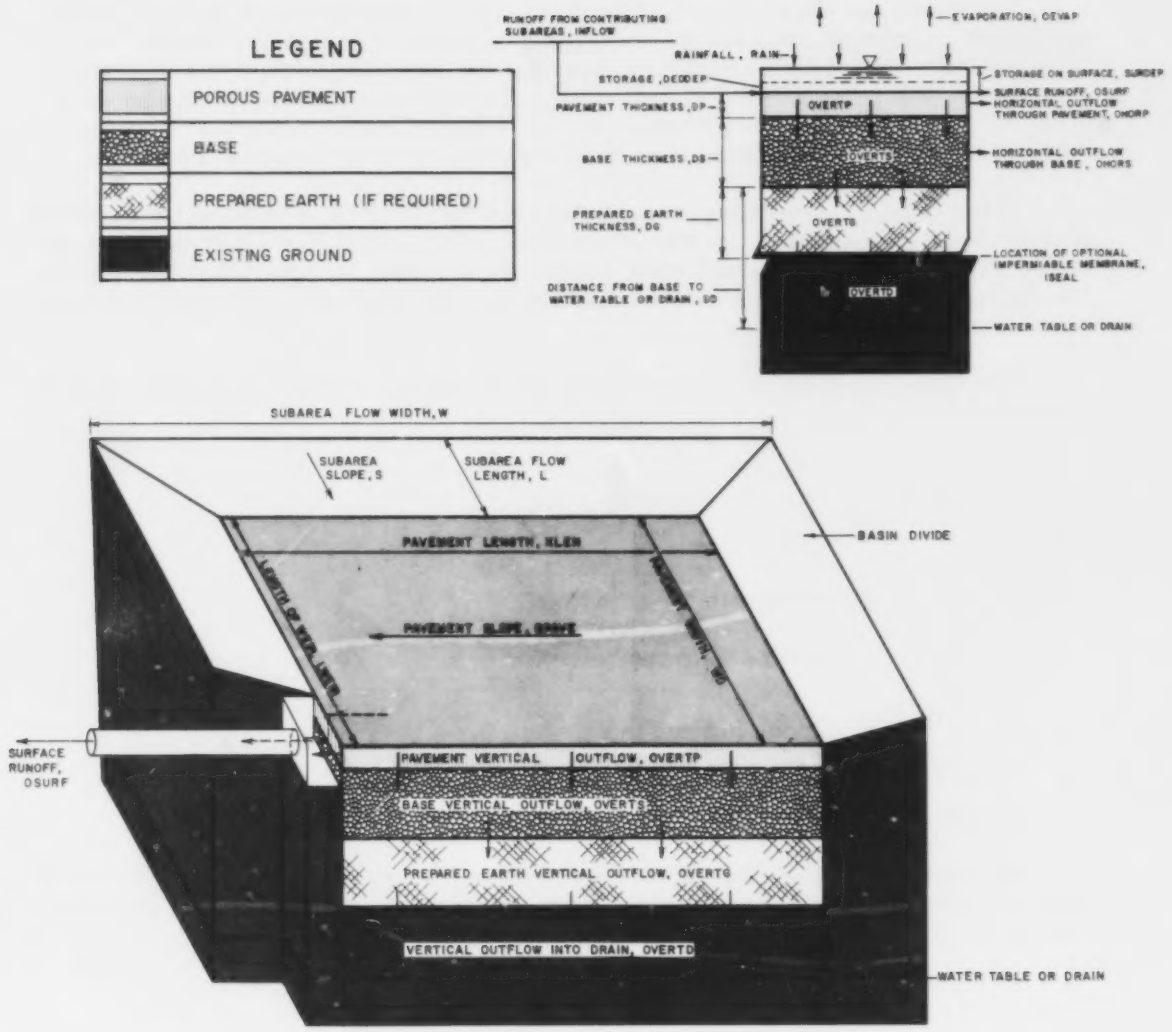


FIGURE 3 HYDROLOGIC MODEL PARAMETERS FOR POROUS PAVEMENTS

HYD = surface runoff hydrograph from contributing areas

Contributing areas to the porous pavement will generally be developed and impervious in nature. Consequently, the surface runoff hydrograph from contributing areas is determined by use of the method developed by Izzard (18). This method, selected for its programming ease, utilizes a dimensionless hydrograph from paved areas as shown in Fig. 4. The key parameters in this method are time to equilibrium, t_e; equilibrium flow, q_e; equilibrium surface detention volume, V_e; the intensity of rainfall, i; and the length of overland flow, L. The following equations define these parameters:

$$q_e = \frac{wiL}{43200}$$

where:

q_e = equilibrium flow, cfs

i = rainfall intensity, inches per hour

L = length of overland flow, feet

w = width of overland flow, feet.

$$V_e = \frac{k L^{1.33} i^{0.33}}{35.1}$$

where:

V_e = equilibrium surface detention volume, cu. ft.

k = an empirically derived, lumped coefficient for the effects of slope and flow retardance of the pavement

$$t_e = \frac{V_e}{30\, q_e}$$

t_e = time to equilibrium, minutes

Using t/t_e values based on the computation interval and Fig. 4, the q/q_e values and the corresponding q values are determined for the rising limb of the hydrograph.

The β factor, defined as

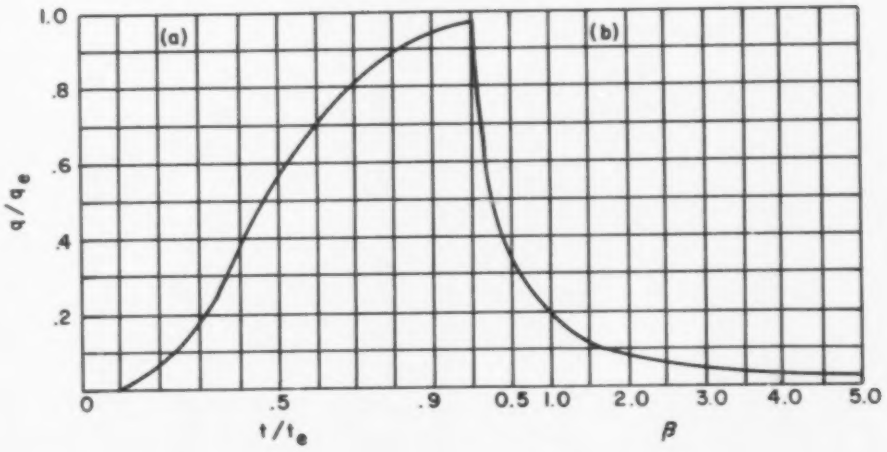


FIGURE 4

IZZARD'S DIMENSIONLESS HYDROGRAPH OF OVERLAND FLOW

$$\beta = \frac{60\, q_e\, t_a}{V_o}$$

where

t_a = time after rainfall has ceased, minutes

V_o = equivalent to V_e without the rainfall intensity component, cu. ft.

is used to determine the q/q_e and corresponding q values for the recession limb of the hydrograph.

If the duration of rainfall is greater than the time required to reach flow equilibrium, ($t_e < t < t_a$), then the q/q_e value remains at a constant value of 0.97 until t_a.

The rainfall hyetograph is input as average intensity per hour for all intervals during which rainfall occurs. Runoff hydrographs are computed for each interval, successively, and summed to determine the cumulative storm hydrograph from contributory areas to the porous pavement. The inflow hydrograph is converted to units of depth based on the area of the porous pavement and computation interval. The rainfall depth onto the porous pavement, PAV, is added to surface runoff depth, HYD, to determine RUNOFF. An alternative user optional input table of RUNOFF depths per computation interval may also be utilized. This option is useful in those instances where storm hydrograph data are available from observation or computed by other methods.

Outflows from the Porous Pavement System

As considered in this model, the outflows from the porous pavement system are composed of four outflow functions defined as follows:

OTOTAL = OVERT + OHOR + OSURF + OEVAP

OVERT is the vertical seepage into the pavement, base, or ground. This seepage is determined as the difference in surface water depth at the beginning and end of each time interval. The variable head permeability equation as defined by Taylor (19) is:

$$K = 2.3 \frac{aL}{A \Delta t} \log \frac{h_1}{h_2}$$

where:

K = permeability of flow element, ft/sec

a = cross-sectional area of surface water, sq ft

A = cross-sectional area of flow element, sq ft

L = thickness of flow element, ft

h_1 = depth of surface water at time t_1, ft

h_2 = depth of surface water at time $t_2 = t_1 + \Delta t$, ft

These parameters are graphically depicted in Fig. 3.

In a porous pavement system, the cross-sectional areas of surface water and flow elements are always equal, and so the equation is reduced to:

$$K = 2.3 \frac{L}{\Delta t} \log \frac{h_1}{h_2}$$

This equation may be rearranged to solve for h_2 as follows:

$$h_2 = \frac{h_1}{10^E}$$

where

$$E = \frac{K \Delta t}{2.3L}$$

Then, vertical seepage is equal to the change in water depth during Δt or,

$$OVERT = h_1 - h_2$$

OHOR is the lateral outflow to a drain or into the natural ground as a result of water storage in the base and pavement. This condition is analogous to bank recharge from a rising stream. In most porous pavement systems, lateral outflow will be negligible because OVERT >> OHOR. However if this condition is not met as in Class C or D soils, then OHOR may be a significant factor. For a homogenous isotropic aquifer of finite width, the influence of each increment of rise in the stream is determined by the following set of equations (20):

$$\frac{d^2h}{dx^2} = \frac{S}{T} \frac{dh}{dt}$$

$$h(0,t) = 0 \text{ for } t \leq 0$$

$$h(0,t) = \Delta H_i \text{ for } t > 0$$

$$\frac{dh(L,t)}{dx} = 0$$

$$h(x,0) = 0$$

where

h	=	hydraulic head or water depth, ft
x	=	distance from boundary, ft
S	=	coefficient of storage of aquifer
T	=	aquifer transmissivity, cfs/ft
ΔH_i	=	change in water depth at boundary, ft
L	+	distance to impermeable boundary or discharge point, ft.

ΔH_i is the increase in stored water depth as a result of vertical drainage from an upper storage volume (previous OVERT). If ΔH_i is negative (after inflow has ceased) water will drain back into the storage volume from the surrounding natural ground. If ΔH_i is 0 then OHOR = 0.

Integrate the first equation and apply boundary conditions to get:

$$\frac{dh}{dx} = \frac{S}{T} \frac{dh}{dt} x$$

The Darcy flow equation can be extended by continuity to define net flow rate as follows:

$$V = K \frac{dh}{dx}$$

$$Q = K A \frac{dh}{dx} = K h w \frac{dh}{dx}$$

$$q = \frac{Q}{w} = K\,h\,\frac{dh}{dx} = T\,\frac{dh}{dx}$$

where:

V	=	velocity of flow, ft/sec
K	=	permeability of flow element, ft/sec
$\frac{dh}{dx}$	=	change in hydraulic grade, ft/ft
Q	=	total mass flow rate, cfs
A	=	total flow area, sq. ft.
h	=	depth of flow, ft.
w	=	width of flow, ft.
q	=	flow rate per unit width, cfs/ft
T	=	transmissivity of flow element, cfs/ft

Then by substitution:

$$q = T\,\frac{S}{T}\,\frac{dh}{dt}\,x = S\,\frac{dh}{dt}\,x$$

define:

$$\frac{dh}{dt} = \frac{h_1 - h_2}{\Delta t} \qquad \text{for } x \simeq 1.0 \text{ ft}$$

and S is the storage coefficient of the natural ground. At a distance x from the porous pavement boundary, the discharge per unit width is defined as:

$$q = S\,\left(\frac{h_1 - h_2}{\Delta t}\right)\,x$$

Because the volume of flow remaining is the only item of interest, the value of x was arbitrarily set equal to 1.0. Then, lateral outflow,

$$OHOR = q\,P\,\Delta t = S\,\left(\frac{h_1 - h_2}{\Delta t}\right)\,P\,\Delta t$$

where:

P = pavement perimeter, ft.

Figure 3 shows how these parameters apply to porous pavement areas. OSURF is the surface runoff resulting from ponding on top of the porous pavement, which occurs either because the inflow rate is greater than the porous pavement permeability or the total storage capacity in the porous pavement system is exceeded. The model requires a depth-storage relationship to determine when the storage is exceeded. On a horizontal pavement, the model determines the depth-storage relationship by use of input pavement and base depths and porosities; on a sloping pavement, this relationship has to be independently computed and input to the model.

The surface runoff from a horizontal pavement is defined by the weir equation:

$$OSURF = CLH^{1.5}$$

where:

C = input weir coefficient

L = input weir length, ft.

H = $h - h_0$, ft.

h_0 = depth of dead surface storage on the porous pavement, ft.

h = depth of flow on the porous pavement, ft.

On a sloping porous pavement, Manning's Equation is used to determine the surface runoff:

$$OSURF = y\,L\,\frac{1.486}{n}\,y^{1.33}\,s^{0.5}$$

where:

y = computed depth of flow, ft.

t = width of flow, ft.

n = input roughness coefficient

s = input energy slope, ft/ft

OEVAP is the volume of water lost to evaporation. This water loss is computed during and after a storm if water remains on the surface i.e. the pavement is flooded. Although the loss during a storm may be negligible, ponded surface water loss after a storm may be significant particularly in arid climates.

Either monthly, weekly or daily evaporation rates may be input to the model; the monthly and weekly rates are divided into average daily rates. The daily evaporation rate may be increased by an input ratio to allow for heat absorption by the dark asphalt. The model only allows for evaporation from 6 a.m. to 8 p.m., with the maximum rate at 2 p.m. As shown in Fig. 5, a triangular distribution of evaporation is developed by the model by use of the equation:

$$E_p = \frac{E_t}{7}$$

where:

E_p = peak evaporation rate, in/hr

E_t = total daily evaporation, in

for $0 < t_c \leq 6$, $E = 0$

for $6 < t_c \leq 14$, $E = E_p \left(\frac{t_c - 6}{8}\right)$

for $14 < t_c \leq 20$, $E = E_p \left(\frac{20 - t_c}{6}\right)$

for $20 < t_c \leq 24$, $E = 0$

where:

t_c = clock time, hours

E = instantaneous evaporation rate

Model Operation

The paths of water flow through the porous pavement system are shown in Fig. 3. For each computational time interval, all inflows and outflows are accounted for. The total runoff hydrograph, in inches per computational time interval, is either input to the model or may be computed as the sum of runoff hydrographs from contributory areas and direct rainfall onto the pavement as described previously.

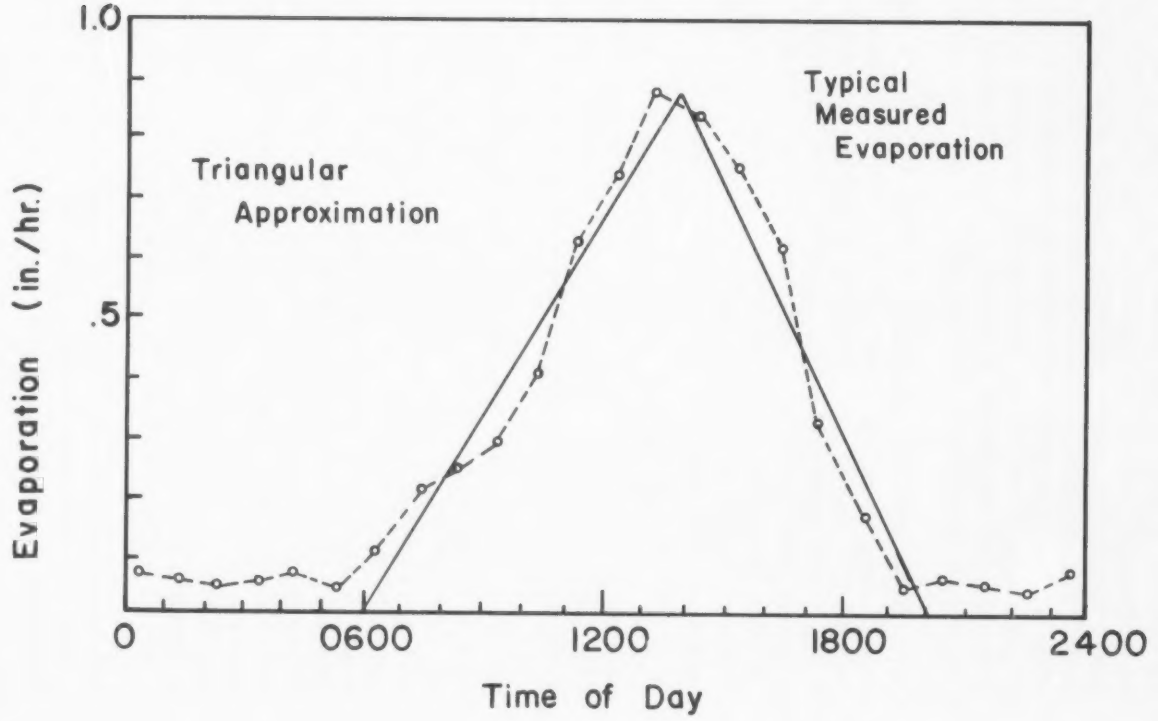


FIGURE 5

TRIANGULAR APPROXIMATION OF EVAPORATION

The following sequential computational steps are then performed:

1. Evaporation losses in inches per computational time interval are computed and subtracted from the sum of the runoff depth and previous surface storage, if any.

2. The volume of runoff after allowing for evaporation is compared to the permeability in inches per time interval of the porous pavement. In general, the permeability is much greater than the inflow runoff rate and all of the water moves into the pavement control volume. In those cases where the permeability has been severely reduced and is less than the runoff rate, the inflow into the pavement and the excess is stored on the surface of the pavement for later computation of surface runoff from the pavement.

3. The inflow into the pavement control volume is added to the storage volume in the pavement and then compared to the permeability, in inches per computational time interval, of the base. If the base permeability is greater than the inflow into the pavement, then all of the flow is transferred into the base control volume. This is true for most porous pavement systems operating according to design. In those instances where the base permeability is less than the inflow volume, the inflow into the base is computed as the vertical seepage into the base. The lateral outflow from the pavement is also computed if an impermeable membrane is not installed along the pavement perimeter. The difference between the inflow into the pavement and the outflows (vertical and lateral) from the pavement is stored in the pavement.

4. The inflow into the base control volume is added to the storage volume in the base and then compared to the permeability in inches per computational time interval, of the natural ground. If the bottom is sealed with an impermeable membrane, then the permeability is set equal to zero, and no flow is lost to the natural ground. The flow volume remaining in the base after vertical seepage into the natural ground is compared to the drain capacity, in inches per computational time interval. If the natural ground permeability and/or drain capacity are inadequate to remove all of the flow in the base, the vertical seepage into the natural ground and drains, as well as the lateral outflow, if any, is computed. The difference between the inflow into the base and the outflows (vertical and lateral) from the base is stored in the base.

5. All stored volumes are compared to available volumes. If storage volume in the base is exceeded, the excess is stored in the pavement; if storage volume in the pavement is exceeded, the

excess is added to the surface storage on the pavement, if any exists. Surface runoff is then computed either as broad channel flow or weir flow from the pavement to an adjacent drainageway.

This computational procedure is repeated for every time interval in the inflow hydrograph. The surface and drain outflows are stored in retrievable arrays. The primary output objective is the surface runoff, if any. However, the other output variables allow for a thorough examination of the hydraulic operational characteristics of the porous pavement system, including the analysis of the desirability or adequacy of the drains and the discharge rate from the drains.

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APPENDIX A

SAMPLE SPECIFICATIONS FOR POROUS ASPHALT PAVEMENT

The following sample specifications are presented in this report to assist the specification writer for whom porous pavement construction is a new area of practice. These specifications will have to be tailored to individual area needs, but sufficient detail is provided so that only minimal changes will have to be made. Consequently, these specifications may have to be reduced in some cases, but precautions must be taken to assure that a contractor understands the exact scope of work, particularly if this is the first attempt at porous pavement construction.

ITEM A: SUBGRADE PREPARATION FOR POROUS PAVEMENT

A.1 DESCRIPTION

The work covered by this item consists of scarifying, blading, and rolling the subgrade to obtain a uniform texture and provide as nearly as practicable a uniform density for the top six inches of the subgrade.

A.2 CONSTRUCTION METHODS

The subgrade shall be shaped in conformity with the typical sections shown on the plans and to the lines and grades established by the Engineer by the removal of existing material or addition of approved material. All unsuitable or otherwise objectionable material shall be removed from the subgrade and replaced with approved material. All holes, ruts and depressions shall be filled with approved material. The surface of the subgrade shall be finished to the lines and grades as established, and be in conformity with the typical sections shown on the plans. Any deviation in excess of one-half (½) inch (1.27 cm) cross-section and in a length of sixteen (16) feet (4.9 m) measured longitudinally shall be corrected by loosening, adding, or removing material, reshaping and compacting by sprinkling and rolling if required to attain but not exceed the density of the natural subgrade. Sufficient subgrade shall be prepared in advance to ensure satisfactory prosecution of the work. The contractor will be required to set blue tops for the subgrade on center-line, at quarter points and curb lines at intervals not exceeding fifty (50) feet (15.2 m).

Material removed may be utilized in the addition of material to the subgrade if approved by the Engineer. All other material required for the completion of the subgrade shall also be subject to approval by the Engineer.

The type of equipment used in subgrade preparation construction shall not cause undue subgrade compaction. Traffic over subgrade shall be kept at a

minimum. Where fill is required, it shall be compacted to a density equal to the undisturbed subgrade, and inherent soft spots corrected.

A.3 MEASUREMENT

All acceptable subgrade preparation will be measured by the square yard as the area for the entire width of the roadway plus twelve inches (30.5 cm) behind each curb for the entire length.

A.4 PAYMENT

This item shall be paid for at the contract unit price bid for "Subgrade Preparation for Porous Pavement," which price shall be full compensation for all work herein specified, including the furnishing of all materials, equipment, tools, and labor and incidentals necessary to complete the work.

Payment shall be made under:

Pay Item No. 240: Subgrade Preparation for Porous Pavement - Per Square Yard (m^2).

ITEM B: STONE BASE COURSE FOR STORMWATER STORAGE

B.1 DESCRIPTION

"Stone Base Course for Stormwater Storage" shall consist of a foundation course for surfacing, pavement or other base courses; shall be composed of crushed stone or gravel, and shall be constructed as herein specified in two courses in conformity with the typical sections shown on the plans and to the lines and grades as established by the Engineer.

B.2 MATERIAL

The material shall be crushed as necessary to meet the requirements hereinafter specified, and shall consist of durable stone or gravel, crushed and/or screened to the required particle size. The material shall be from approved sources.

Testing of flexible base materials shall be in accordance with the following Texas Highway Department standard laboratory test procedures:

1)	Preparation for Soil Constants and Sieve Analysis	TEX-101-E
2)	Sieve Analysis	TEX-110-E
3)	Wet Ball Mill	TEX-116-E

Unless otherwise specified on the plans, all base material will be stockpiled after crushed; tested by the testing agency designated by the City of _____ and approved by the City of _____ prior to being hauled to the project site.

The material, when properly tested, shall meet the following requirements:

Course	Sieve Size	Retained on Sieve, Percent
Stone Base Course	2½"	0
	1½"	100
Stone Top Course	5/8"	0
	3/8"	100
Max. Wet Ball Mill		50

Unless otherwise shown on plans, the maximum increase in material passing the Number 40 sieve resulting from the Wet Ball Mill Test shall not exceed 20.

B.3 CONSTRUCTION METHODS

(1) Preparation of Subgrade

The street shall be prepared and shaped in conformity with Item 240, "Subgrade Preparation for Porous Pavement" and the typical sections shown on plans and to the lines and grades as established by the Engineer. The surface of the subgrade shall be finished to line and grade as established and in conformity with the typical section shown on plans, and any deviation in excess of ¼ inch (0.6 cm) in cross-section and in a length of 10 feet (3.0 m) measured longitudinally shall be corrected by loosening, adding or removing material and reshaping. Sufficient subgrade shall be prepared in advance to ensure satisfactory prosecution of the work. Material excavated in the preparation of the subgrade shall be utilized in the construction of slopes or otherwise disposed of as directed, and any additional material required for the completion of slopes shall be secured from sources indicated on plans or designated by the Engineer. Blue tops shall be set by the contractor for subgrade on centerline, quarter points and curb lines at intervals not exceeding 50 feet (15.2 m).

(2) Stone Base Course

Immediately before placing the stone base material, the subgrade shall be checked as to conformity with grade and section.

The material shall be delivered in approved vehicles of a uniform capacity and it shall be the charge of the Contractor that the required

amount of specified material shall be delivered in each 100-foot (30.5 m) station.

Stone base course shall be laid over a dry subgrade to the depth shown in drawings, in lifts to lay naturally compacted. The stone base course is not to be rolled or compacted and is to be kept clean from debris, clay, and eroding soil.

(3) Stone Top Course

This course is to be two inches in depth. Construction methods shall be the same as prescribed for the stone base course. Blue tops shall be set by the contractor for finished base grade on center-line and intermediate points not exceeding 11 feet (3.4 m) between points at 50-foot (15.2 m) intervals.

B.4 MEASUREMENT

"Stone Base Course" including the "Stone Top Course" will be measured by the square yard (m^2) at depths specified in the proposal for the area of Parking Lot as shown on the typical sections of the plans or otherwise provided for in the contract documents, complete in place; by the cubic yard (m^3), loose vehicle measurement; or by the cubic yard (m^2), complete in place, as indicated in the proposal.

B.5 PAYMENT

This item will be paid for at the contract unit price bid for "Stone Base Course," which price shall be full compensation for all work herein specified, including the furnishing, hauling, and placing of all materials, for all water required and for all equipment, tools, labor and incidentals necessary to complete the work.

Payment will be made under:

Pay Item No. 250-A: Stone Base Course (complete in place) - Per Square Yard (m^2), or
Per Item No. 250-B: Stone Base Course (loose vehicle measurement) - Per Cubic Yard (m^3), or
Pay Item No. 250-C: Stone Base Course (complete in place) - Per Cubic Yard (m^3).

* This item must be verified for local requirements and site conditions.

ITEM C: HOT MIX POROUS ASPHALT PAVEMENT

C.1 DESCRIPTION

This item shall consist of a surface course as shown on the plans, composed of a lightly compacted mixture of mineral aggregate and asphaltic material.

The pavement shall be constructed on the previously completed and approved subgrade and stone base course as herein specified and in accordance with the details shown on the plans.

C.2 MATERIALS

(1) Coarse Aggregate

The mineral aggregate shall be composed of a coarse aggregate, a fine aggregate, and if required, a mineral filler. Samples of coarse aggregate and mineral filler shall be submitted for testing as directed by the Engineer and approval of both material and of the source of supply must be obtained from the Engineer prior to delivery.

(a) Coarse Aggregate

Coarse aggregate shall be that part of the aggregate retained on the No. 8 sieve; shall consist of clean, tough, durable fragments of crushed stone, or crushed gravel, as hereinafter specified of uniform quality throughout.

When the coarse aggregate is tested in accordance with Test Method Tex-217-F* (Part I, Separation of Deleterious Material), the amount of organic matter, clay, loam or particles coated therewith or other undesirable materials shall not exceed two percent and when remaining part of the sample is further tested in accordance with Test Method Tex-127-F* (Part II, Decantation), the amount of material removed shall not be more than two percent.

The coarse aggregate shall have an abrasion of not more than forty percent loss by weight when subjected to the Los Angeles Abrasion Test, Test Method Tex-410-A*.

Unless specified otherwise, gravel shall be so crushed that seventy-five percent of the particles retained on the No. 4 sieve shall have more than one crushed face when tested in accordance with Test Method Tex-413-A* (Particle Count).

(b) Fine Aggregate

The fine aggregates shall be that part of the aggregate passing the No. 8 sieve and shall consist of sand, screenings, or combination thereof as hereinafter specified of uniform quality throughout.

Fine aggregate shall consist of durable particles, free from injurious foreign matter. Screenings shall be of the same or similar materials as specified for coarse aggregate. The plasticity index of that part of the fine aggregate pasing the No. 40 sieve shall be not more than 6 when tested in accordance with Test Method Tex-106-E*. Fine aggregate from each source shall meet plasticity requirements.

Where stone screenings are specified for use, the stone screenings shall meet the following grading requirements unless otherwise shown on plans:

	Percent by Weight
Passing the ½" Sieve	100
Passing the No. 200 Sieve	10-30

When authorized by the Engineer, stone screenings containing particles larger than ½" may be used but only that portion of the material passing the 3/8" sieve shall be considered as fulfilling the requirements for screenings when a minimum percentage of screenings is specified for a particular mixture.

(c) Mineral Filler

Mineral filler shall consist of thoroughly dry stone dust, slate dust, portland cement, fly ash or other mineral dust approved by the Engineer. The mineral filler shall be free from foreign and other injurious matter.

When tested by Test Method Tex-200-F* (Dry Sieve Analysis), it shall meet the following grading requirements:

	Percent by Weight
Passing a No. 30 Sieve	95 to 100
Passing a No. 80 Sieve, not less than	75
Passing a No. 200 Sieve, not less than	55

(2) Asphaltic Material for Porous Asphalt Paving Mixture

Asphalt for the paving mixture shall be asphalt cement, viscosity grade AC-20* and shall meet the requirements of the Item, "Asphalts, Oil and Emulsions." The Contractor shall notify the Engineer of the source of his asphaltic material prior to production of the asphaltic mixture and this source shall not be changed during the course of the project except on written permission of the Engineer.

The paving mixture shall consist of a uniform mixture of coarse aggregate, fine aggregate, asphaltic material and mineral filler, if required.

The grading of each constituent of the mineral aggregate shall be such as to produce, when properly proportioned, a mixture which, when tested in accordance with Test Method Tex-200-F* (Dry Sieve Analysis), will conform to the limitations for master grading given below:

	Percent by Weight
Passing ½" Sieve	100
Passing 3/8" Sieve, Retained on No. 4 Sieve	40-65
Passing No. 4 Sieve, Retained on No. 8 Sieve	3-35
Passing No. 8 Sieve, Retained on No. 16 Sieve	1-20
Passing No. 16 Sieve, Retained on No. 200 Sieve	0-10
Passing No. 200 Sieve	2-5

The asphaltic material shall form from 5.5 to 6.0 percent of the mixture by weight unless specified otherwise on the plans.

The Engineer will designate the exact grading of the aggregate and asphalt content, within the above limits, to be used in the mixture. The paving mixture produced should not vary from the designated grading and asphalt content by more than the tolerances allowed herein; however, the mixture produced shall conform to the limitations for master grading specified above.

	Percent by Weight
Passing ½" Sieve, Retained on 3/8" Sieve	± 5
Passing 3/8" Sieve, Retained on No. 4 Sieve	± 5
Passing No. 4 Sieve, Retained on No. 8 Sieve	± 5
Total Retained on No. 8 Sieve	± 5
Passing No. 8 Sieve, Retained on No. 16 Sieve	± 3
Passing No. 16 Sieve, Retained on No. 200 Sieve	± 3
Passing No. 200 Sieve	± 3
Asphalt Material	± 0.25

Should the paving mixture produced vary from the designated grading and asphalt content by more than the above tolerances, proper changes are to be made until it is within these tolerances.

Samples of the mixture when tested in accordance with Test Method Tex-210-F* shall not vary from the grading proportions of the aggregate and the asphalt content designated by the Engineer by more than the respective tolerances specified above and shall be within the limits specified for master grading.

C.3 EQUIPMENT

(1) Mixing Plants

Mixing plants that will not continuously meet all the requirements of this specification shall be condemned.

Mixing plants may be either the weight-batching type or the continuous mixing type. Both types of plants shall be equipped with satisfactory conveyors, power units, aggregate handling equipment, aggregate screens and bins and shall consist of the following essential pieces of equipment:

(a) Weight-Batching Type

Cold Aggregate Bin and Proportioning Device. The cold aggregate bins or aggregate stockpiles shall be of sufficient number and size to supply the amount of aggregate required to keep the plant in continuous operation. The proportioning device shall be such as will provide a uniform and continuous flow of aggregate in the desired proportion to the plant.

Dryer. The dryer shall be of the type that continually agitates the aggregate during heating and in which the temperature will be so controlled that aggregate will not be injured in the necessary drying and heating operations required to obtain a mixture of the specified temperature.

The burner, or combination of burners, and type of fuel used shall be such that in the process of heating the aggregate to the desired or specified temperatures, no residue from the fuel shall adhere to the heated aggregate.

A recording thermometer shall be provided which will record the temperature of the aggregate when it leaves the dryer. The dryer shall be of sufficient size to keep the plant in continuous operation.

Screenings and Proportioning. The screening capacity and size of the bins shall be sufficient to screen and store the amount of aggregate required to properly operate the plant and keep the plant in continuous operation at full capacity. Proper proportions shall be made to enable inspection forces to have easy and safe access to the proper location on the mixing plant where accurate representative samples of aggregate may be taken from the bins for testing. Separation of hot bin into compartments will not be required providing uniform grading and asphalt content are consistently produced in the completed mix.

Aggregate Weigh Box and Batching Scales. The aggregate weigh box and batching scales shall be of sufficient capacity to hold and weigh a complete batch of aggregate. The weigh box and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment."

Asphaltic Material Bucket and Scales. The asphaltic material bucket and scales shall be of sufficient capacity to hold and weigh the necessary asphaltic material for one batch. If the material is measured by weight, the bucket and scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment."

If a pressure type flow meter is used to measure the asphaltic material, the requirements of the Item, "Weighing and Measuring Equipment" shall apply.

Mixer. The mixer shall be of the pug mill type and shall have a capacity of not less than 20 cubic feet (0.57 m^3) unless otherwise shown on the plans. The number of blades and the position of same shall be such as to give a uniform and complete circulation of the batch in the mixer. The mixer shall be equipped with an approved spray bar that will distribute the asphaltic material quickly and uniformly throughout the mixer. Any mixer that has a tendency to segregate the mineral aggregate or fails to secure a thorough and uniform mixing with the asphaltic material shall not be used. This shall be determined by mixing the standard batch for the required time, then dumping the mixture and taking samples from its different parts. This will be tested by the extraction test and must show that the batch is uniform throughout. All mixers shall be provided with an automatic time lock that will lock the discharge doors of the mixer for the required mixing period. The dump door or doors and the shaft seals of the mixer shall be tight enough to prevent spilling of aggregate or mixture from the pug mill.

(b) Continuous Mixing Type

Cold Aggregate Bin and Proportioning Device. Same as for weight-batching type of plant.

Dryer. Same as for weight-batching type of plant.

Screening and Proportioning. Same as for weight-batching type of plant.

Aggregate Proportioning Device. The hot aggregate proportioning device shall be so designed that when properly operated a uniform and continuous flow of aggregate into the mixer will be maintained.

Asphaltic Material Spray Bar. The asphaltic material spray bar shall be designed such that the asphalt will spray uniformly and continuously into the mixer.

Asphaltic Material Meter. An accurage asphaltic material recording meter shall be placed in the asphalt line leading to the spray bar so that the cumulative amount of asphalt used can be accurately determined. Provisions of a permanent nature shall be made for checking the accuracy of the meter output. The asphalt meter and line to the meter shall be protected with a jacket of hot oil or other approved means to maintain the temperature of the line and meter near the temperature specified for the asphaltic material.

If a pressure type flow meter is used to measure the asphaltic material, the requirements of the Item "Weighing and Measuring Equipment" shall apply.

Mixer. The mixer shall be of the pug mill continuous type and shall have a capacity of not less than 40 tons (36.3 Mg metric ton) of mixture per hour. Any mixer that has a tendency to segregate the aggregate or fails to secure a thorough and uniform mixing of the aggregate with the asphaltic material shall not be used. The dam gate at the discharge end of the pug mixer and/or pitch of the mixing paddles shall be so adjusted as to maintain a level of mixture in the pug mixer between the paddle shaft and the paddle tips (except at the discharge end).

Truck Scales. A set of standard platform truck scales, conforming to the Item, "Weighing and Measuring Equipment," shall be placed at a location approved by the Engineer.

(2) Asphaltic Material Heating Equipment

Asphaltic material heating equipment shall be adequate to heat the amount of asphaltic material required to the desired temperature. Asphaltic material may be heated by steam coils which shall be absolutely tight. Direct fire heating of asphaltic material will be permitted, provided the heater used is manufactured by a reputable concern and there is positive circulation of the asphalt throughout the heater. Agitation with steam or air will not be permitted. The heating apparatus shall be equipoped with a recording thermometer with a 24-hour chart that will record the temperature of the asphaltic material at the highest temperature.

(3) Spreading and Finishing Machine

The spreading and finishing machine shall be of a type approved by the Engineer, shall be capable of producing a surface that will meet the requirements of the typical cross-section and a surface test, when required, and when the mixture is dumped directly into the finishing machine shall have adequate power to propel the delivery vehicles in a satisfactory manner. The finishing machine shall be equipped with a flexible spring and/or hydraulic type hitch sufficient in design and capacity to maintain contact between the rear wheels of the hauling equipment and the pusher rollers of the finishing machine while the mixture is being unloaded.

The use of any vehicle which requires dumping directly into the finishing machine and which the finishing machine cannot push or propel in such a manner as to obtain the desired lines and grades without resorting to hand finishing will not be allowed.

Automatic screed controls, if required, shall meet the requirements of the Item, "Automatic Screed Controls for Asphaltic Concrete Spreading and Finishing Machines."

(4) Pneumatic Tire Rollers

The rollers shall be acceptable light pneumatic tire rollers conforming to the requirements of the Item, "Rolling (Pneumatic Tire)," unless otherwise specified on plans.

The tire pressure of each tire shall be adjusted as directed by the Engineer and this pressure shall not vary by more than 5 pounds per square inch (34.5 kP2, kilo pascal).

(5) Two Axle Tandem Roller

This roller shall be an acceptable power driven tandem roller weighing not less than 6 tons (5.4 Mg), or more than 10 tons (9.1 Mg).

(6) Three Wheel Roller

This roller shall be an acceptable power driven three wheel roller weighing not more than 10 tons (9.1 Mg).

(7) All Equipment shall be maintained in good repair and operating condition and shall be approved by the Engineer.

(8) Alternate Equipment

When permitted by the Engineer, in writing, equipment other than that specified, which will consistently produce satisfactory results, may be used.

C.4 STOCKPILING, STORAGE, PROPORTIONING AND MIXING

(1) Aggregate Storage

If the mineral aggregates are stored or stockpiled, they shall be handled in such a manner as to prevent segregation, mixing of the various materials or sizes, and contamination with foreign materials. The grading of aggregates proposed for use and as supplied to the mixing plant shall be uniform. Suitable equipment of acceptable size shall be furnished by the Contractor to work the stockpiles and prevent segregation of the aggregates.

(2) Storage and Heating of Asphaltic Materials

The asphaltic material storage shall be ample to meet the requirements of the plant. Asphalt shall not be heated to a temperature in excess of that specified in the Item, "Asphalts, Oils and Emulsions." All equipment used in the storage and handling of asphaltic material shall be kept in a clean condition at all times and shall be operated in such a manner that there will be no contamination with foreign matter.

(3) Feeding and Drying of Aggregates

The feeding of various sizes of aggregate to the dryer shall be done through the cold aggregate bin and proportioning device in such a manner that a uniform and constant flow of materials in the required proportions will be maintained. When specified on the plans, the cold aggregate bins

shall be charged by use of a clamshell, dragline, shovel or front end loader. The aggregate shall be dried and heated to the temperature necessary to produce a mixture having the specified temperature.

(4) Proportioning

The proportioning of the various materials entering the asphaltic mixture shall be as directed by the Engineer and in accordance with these specifications. Aggregate shall be proportioned by weight using the weigh box and batching scales herein specified when the weight-batch type of plant is used and by volume using the hot aggregate proportioning device when the continuous mixer type of plant is used. The asphaltic material shall be proportioned by weight or by volume based on weight using the specified equipment.

(5) Mixing

(a) Batch Type Mixer

In the charging of the weigh box and in the charging of the mixer from the weigh box, such methods or devices shall be used as are necessary to secure a uniform asphaltic mixture. In introducing the batch into the mixer, the mineral aggregate shall be introduced first; shall be mixed thoroughly for a period of 5 to 20 seconds, as directed, to uniformly distribute the various sizes throughout the batch before the asphaltic material is added; the asphaltic material shall then be added and the mixing continued for a total mixing period of not less than 30 seconds. This mixing period may be increased if, in the opinion of the Engineer, the mixture is not uniform.

(b) Continuous Type Mixer

The amount of aggregate and asphaltic material entering the mixer and the rate of travel through the mixer shall be so coordinated that a uniform mixture of the specified grading and asphalt content will be produced. Checks on asphalt used shall be made at least twice daily by comparing the asphalt used in ten loads of completed mix as shown on the asphalt recording meter and the design amount for these ten loads. The acceptable percent of variation between the asphalt used and the design amount will be as shown on the plans or as determined by the Engineer.

(c) The Mixture produced from each type of mixer shall not vary from the specified mixture by more than the tolerances herein specified.

(d) The Surface Mixture from each type of mixer will not exceed a temperature of 260° F (127° C) and shall be specified by the Engineer. The temperature of the mixture will not be lower than 180° F (82° C) when placed on the road.

C.5 CONSTRUCTION METHODS

(1) The surfacing mixture shall not be placed when the air temperature is below 50° F (10° C) and is falling, but it may be placed when the air temperature is above 40° F (4° C) and rising. The air temperature shall be taken in the shade away from artificial heat. It is further provided that the surfacing mixture shall be placed only when the humidity, general weather conditions and temperature and moisture condition of the pavement surface, in the opinion of the Engineer, are suitable.

(2) Transporting the Surface Mixture

The mixture, prepared as specified above, shall be hauled to the work in tight vehicles with smooth dump beds that have been previously cleaned of all foreign material. The dispatching of vehicles shall be arranged so that all material delivered may be placed, and all rolling shall be completed during daylight hours. In cool weather or for long hauls, canvas covers and insulating of the truck bodies may be required. The inside of the truck body shall be sprayed with a non-petroleum relase agent satisfactory to the Engineer, if necessary, to prevent the mixture from adhering to the body.

(3) Placing

The asphaltic mixture shall be dumped directly into the specified spreading and finishing machine and spread on the approved prepared surface in such a manner that, when properly compacted, the finished surface will be smooth and of uniform texture and density. The spreading and finishing machine shall be operated at a speed satisfactory to the Engineer. During application of asphaltic material, care shall be taken to prevent splattering of adjacent pavement, curb and gutter and structures.

(4) Compacting

(a) As directed by the Engineer, the surface mixture shall be compressed lightly and uniformly with the specified rollers and/or other approved rollers.

(b) Compaction of the surface course shall be done while the surface is cool enough to resist the roller used. One or two passes by the

roller is all that is required, as excess rolling could cause a reduction in surface course porosity.

(c) The motion of the rollers shall be slow enough at all times to avoid displacement of the mixture. If any displacement occurs, it shall be corrected at once by the use of rakes and of fresh mixture where required. To prevent adhesion of the surfacing mixture to the roller, the wheels shall be kept thoroughly moistened with a soap-water solution. Necessary precautions shall be taken to prevent the dropping of gasoline, oil, grease or other foreign matter on the pavement, either when the rollers are in operation or when standing.

(5) Surface Tests

The surface of the pavement, after compaction, shall be smooth and true to the established line, grade and cross-section, and when tested with a 10-foot (3.0 m) straight-edge, the maximum deviation shall not exceed ¼ inch (6 mm) in 10 feet (3.0 m), and any point in the surface not meeting this requirement shall be corrected as directed by the Engineer. The completed surface shall meet the approval of the Engineer for riding surface finish and appearance.

(6) After final rolling, no vehicular traffic of any kind shall be permitted on the porous pavement until cooling or hardening has taken place, as directed by the Engineer, but in no case less than six hours.

C.6 MEASUREMENT

(1) The surfacing mixture will be measured separately by the ton of 2,000 pounds (907 kilograms, Kg) of "Asphalt" and by the cubic yard of dry, loose "aggregate" of the type actually used in the completed and accepted work in accordance with the plans and specifications for the project. The volume of aggregate in the compacted mix shall be calculated from the measured weights of the surfacing mixture by use of the following formula:

$$V = \frac{(W - A)}{(27)K}$$

V = Cubic Yards of aggregate, dry, loose
W = Total weight of surfacing mixture in pounds (Kg)
A = Weight of Asphalt in pounds (Kg)
K = Unit Weight of Aggregate in pounds per cubic foot (Kg/m^3)

The value "K" shall be the average of two or more tests determined by the Engineer in the following manner:

At the beginning of plant operations, a specified weight of dried mineral aggregate shall be placed in an acceptable container that will contain a minimum volume of three cubic yards (2.3 m^3). The aggregate shall be leveled or "struck-off" and measured, to determine the volume of the mineral aggregate, in cubic feet (m^3). The unit weight of the mineral aggregate shall be obtained by dividing the specified weight of dried aggregate in pounds (Kg) by the measured volume in cubic feet (m^3). The value "K" is an average of two or more of the above-described tests.

The value "K" shall be checked a minimum of one time for each 3,000 cubic yards (2,294 m^3) of mineral aggregate. If, in the opinion of the Engineer or the Contractor's representative, the value of "K" has changed, a check test shall be made. A new value for "K" shall be determined if the checked value of "K" varies more than two percent (plus or minus) from the value being used.

The weight, "W," if mixing is done by a continuous mixer, will be determined by truck scales. The weight, if batched, will be determined on batch scales and records of the number of batches, batch designs and weight of "Asphalt" and "Aggregate" shall be kept.

C.7 PAYMENT

(1) The work performed and materials furnished as prescribed by this item and measured as provided under "Measurement," will be paid for at the unit prices bid for "Asphalt" and "Aggregate," of the types specified, which prices shall each be full compensation for quarrying, furnishing all materials and freight involved; for all heating, mixing, hauling, cleaning the existing pavement, placing asphalt-aggregate surfacing mixture, rolling and finishing; and for all manipulations, labor, tools, equipment and incidentals necessary to complete the work.

(2) All templates, straight-edges, scales and other weighing and measuring devices necessary for the proper construction, measuring and checking of the work shall be furnished, operated and maintained by the Contractor at his expense.

* This item must be verified for local requirements and site conditions.

APPENDIX B

HYDROLOGIC SOIL GROUP CLASSIFICATION

Aastad B
Aberdeen D
Abilene C
Abington B
Acadia D
Acme B
Acton B
Adair D
Adams A
Adamsville C
Ade A
Adel B
Adelanto B
Adelphia B
Adler C
Adolph D
Afton D
Agar B
Agate C
Agawam B
Agency C
Agnew B
Aguadilla A
Aguilita C
Aguirre D
Ahmeek B
Ahnberg C
Ahtanum C
Alken B
Alrmont B
Akaka B
Akan C
Akaska B
Aluchua B
Alaeloa B
Alama C
Alamance C
Alamosa C
Albaton D
Albemarle B
Albertville C
Albia C
Albion B
Alcester B
Alcoa B
Alden D
Alderwood B
Aldino D
Alexandria B
Alexis B
Alford B
Algarrobo D
Algiers D
Alicel B
Allard B
Allegheny B
Allen B
Allendale C
Allenwood B
Alligator D
Allis C
Allison C
Allouez B
Alma C
Almena C
Almirante D
Almo D
Almy G
Alonso C
Alps C
Alsen C
Altamaha D
Altamont C
Altavista B
Alto C
Alton B
Altoona C
Altura B
Altvan B
Alvin B
Alvira C
Amelu D
Amrillo B
Amboy B
Amelia C
Amenia B
Americus A
Ames C
Amite .B
Amity C
Amsterdam B
Andover D
Andres B
Angie C
Angola C
Ankeny A
Annadale B
Anoka A
Anselmo B
Anthony G
Antigo B
Apache B
Apakule B
Apishapa C
Apison C
Applegate C
Appling B
Arch B
Archer C
Arenzville B
Argyle B
Ark C
Arkport B
Arland B
Armagh D
Armer C
Armour B
Armuchee C
Arnold A
Arnot C
Arredondo A
Artesia C
Arvada D
Arveson D
Arzell D
Asa B
Asbury B
Ascalon B
Ashby C
Ashe B
Ashkum C
Ashley A
Ash Springs C
Ashton B
Ashuelot C
Ashwood D
Asotin B
Assumption B
Astoria B
Athelwold B
Athena B
Atherton D
[1]Athol B
Atkins D
Atterberry B
Atwood B
Auburn C
Auburndale D
Au Gres C
Augusta C
Aurora C
Austin B
Ava C
Avalanche B
Avery B
Avon B
Avonburg D
Axtell D
Ayr B

Babylon A
Baca B
Bagnell D
Bainville B
Baker C
Balch A
Baldock B
Baldwin C
Balfour B
Balm A
Balmorhea D
Bangor B
Banks A
Bannerville C
Baraboo B
Barbour B
Barbourville B
Barclay C
Barnard C
Barnes B
Barneston A
Barnett D
Barney A
Barnhardt A
Barnstead B
Barrances D
Barron C
Barronett C
Barth B
Bartle D
Basher B
Bass B
Bastrop B
Batavia B
Bates B
Bath C
Baudette B
Baugh C
Baxter B
Bayamon B
Bayard A
Bayboro D
Bayside C
Beadle C
Bearden C
Beardstown C
Bear Lake D
Bear Prairie B
Beatty B
Beaucoup C
Beauford D
Beaumont D
Beauregard C
Beaver B
Beaverhead B
Becket C
Beckton D
Beckwith D
Bedford C
Bedington B
Beecher C
Beechy D
Belfast D
Belfore C
Belgrade B
Belknap C
Bell D
Belle R
Bellingham D
Belmont B
Beltrami B
Beltsville C
Belvoir C
Benevola B
Benfield C
Benld D
Bennington C
Benolt D
[2]Benson C
Bentonville C
Beotia B
Berg C
Bergland D
Berkeley C
Berks C
Berkshire B
Burmudian B
Bernard D
Bernardston C
Berlen B
Berthoud B
Bertie C
Bertolotti A
Bertrand B
Berwyn C
Bethany C
Bethel D
Beulah B
Beverly A
Bewleyville B
Bibb D
Bickleton B
Biddeford D
Bienville B
Biggs A
Biggsville B
Big Horn C
Billett A
Billings D
Binnsville C
Bippus B
Birds C
Birdsall D
Birdsboro B
Birkbeck B
Biscay D
Bitterroot C
Blacklock D
Blackwater D
Bladen D
Blago D
Blain D
Blair C
Blairton C
Blakeland A
Blakely B
Blanchard A
Blanco B
Bland C
Blandford C
Blanding B
Blanket D
Blanton A
Blencoe C
Blichton C
Blockton C
Blodgett B
Blomford B
Bloomfield A
Bloomington B
Blount C
Blue Earth D
Bluffton D
Blufford D
Bobtail C
Bodine B
Bogota C
Bohemian B
Bold B
Bolivia B
Bolton B
Bombay C
Bonaccord D
Bonaparte A
Bonham B
Bonilla B
Bonita D
Bonner B
Bonneville A
Bonnie D
Bono D
Bonpas B
Boomer C
Boone A
Bordeaux B
Bosket B
Boswell D
Bow D
Bowdoin D
Bowdre C
Bowie B
Bowmansville B

Boyd D
Boyer B
Boynton C
Bozarth C
Bozeman B
Bracaville B
Bracken D
Brackett C
Braddock B
Braden C
Bradenton C
Bradley B
Brady B
Braham B
Brallier A
Brandon B
Brandywine C
Branford B
Brashear C
Bratton B
Braxton B
Brayton C
Brazito A
Brazos B
Brecknock C
Breece B
Breese D
Bremer B
Bremo C
Brennan B
Brenner C
Brenton B
Bresser B
Brewer D
Brewster C
Brickton C
Bridgehampton B
Bridgeport B
Bridger B
Bridgeville B
Briggs A
Briggsdale C
Brill B
[2]Brimfield C
Brimley B
Brinkerton D
Briscoe B
Brittain C
Broadbook C
Broadview C
Brockport C
Brooke C
Brookfield B
Brookings B
Brooklyn D
Broodston B
Broodsville D
Broughton B
Broward C
Brownfield A
Browning B
Brownlee C
Bruno A
Bryce D
Bub C
Buchanan C
Buckingham C
Buckland C
Buckley D
Buckner A
Bucks B
Bucods A
Bude C
Buncombe A
Bunkerville D
Buchard B
Burdett C
Burgess B
Burgin D
Burke B
Burkhardt B
Burleson D
Burnham D
Burnside D
Burnsville B
Burnt Fork B
Burrell C
Burton B
Buse B
Butler D
Butlertown C
Butte B
Buxin D
Buxton C
Byars D
Byrds D

Cabinet C
Cabo Rojo C
Cabot C
Cacapon D
Caddo C
Cagey D
Caguas D
Cahaba B
Cajon A
Callas B
Caldwell B
Calhoun D
Califon C
Calloway C
Calvert D
Calverton C
Calvin C
Camaguey D
Camas A
Cambridge C
Camden B
Cameron C
Camillus C
Camp B
Campo C
Camroden C
[2]Canaan C
Canadian B
Canadice C
Canadalgua C
Canaserage B
Cane B
Caneadea C
Caneyville C
Canfield B
Canoncity D
Canyon C
Cape Fear D
Capron B
Capshaw C
Captina C
Capulin B
Carbo C
Cardiff B
Cardington C
[2]Carey B
Caribou B
Carisle D
Carlsborg A
Carlton B
Carmi B
Carnegie B
Carnero C
Caroline C
Carrington B
Carrizo A
Carrol D
Carson D
Carstairs C
Carver A
Carytown D
Casa B
Casa Grande C
Cascade C
Casco A
Casey C
Cashmere A
Cashton D
Cass A
Cassville B
Castana B
Castle D
Castner C
Catalina C
Catalpa C
Catano A
Cataula C
Cathcart C
Catlett C
Catlin B
Catoctin C
Catron D
Catskill C
Cattaraugus B
Cave C
Cavode C
Cavot B
Cavour D
Cayagua C
Caylor B
Cayucos D
Cayuga C
Cazenovia C
Cecil B
Celina B
Center C
Centerton B
Central A
Chagrin B
Chalfont D
Chama B
Chamber D
Chamberino C
Chamokane B
Chandler C
Channahon B
Charlton C
Charleston C
Charlos B
Charlotte D
Charlton B
Chaseburg B
Chastain D
[2]Chatfield C
Chatsworth D
Chattahoochee B
Chauncey C
Chehalis B
Chelsea A
Chemawa B
Chanango B
Chaney B
Chenoweth B
Cherette A
Cherokee D
Cherry B
Cherryhill B
Cheshire B
Chester B
Chesterfield B
Chetek A
Chewacla C
Chewelah B
Cheyenne B
Chickasha B
Chiefland A
Chigley C
Chilgren C
Chilhowie D
Chili B
Chilliisquaque C
Chillum C
Chilmark C
Chilo D
Chipeta A
Chippewa D
Chiricahua D
Choctaw B
Choptank A
Choteau C
Christian B
Christiana C
Christianburg D
Churchill D
Ciales B
Cialitos C
Cicero C
Cincinnati B
Cinebar A
Cintrona D
Cisne D
Cispus A
Clackamas C
Claiborne B
Clallam C
Clarence D
Clareville C
Clarinda D
Clarion B
Clark Fork B
Clarksburg C
Clarksdale C
Clarkson C
Clarksville B
Clary B
Clatsop D
Claverack B
Clawson C
Clayton C
Cleaver D
Cleburne B
Cle Elum B
Cleman B
Clement C
Cleora B
Clermont D
Clifton B
Climax D
Clinton B
Clio C
Clipper C
Clodine B
Cloquallum C
Cloquet B
Cloud D
Clover Creek C
Clovis B
Clyde C
Clymer B
Coamo C
Cobb B
Cochise B
Cocoa B
Cody A
Coeburn C
Cogswell C
Cokedale C
Coker D
Cokesbury D
Colbert D
Colby B
Colden D
Coldwater D
Colebrood Loamy Fine Sand A
Colebrook Fine Sandy Loam B
Coleman B
Colemantown D
Colfax C
Colinas C
Collamer B
Collington B
Collins C
Collinsville C
Colo C
Coloma A
Colonie A
Coloso D
Colosse A
Colp D
Colrain B
Colton A
Colts Neck B
Columbia B
Colville B
Colwood k
Colyer C
Comfrey C
Comly C
Commerce C
Comoro A
Compton B

Conant B
Conassuaga C
Concord D
Condit D
Condon B
Conestoga B
Conesus C
Congaree B
Conley C
Conotton B
Conover B
Conowingo B
Constable A
Continental C
Conway C
Cook D
Cookeville B
Cookport C
Coolidge B
Coolville C
Cooney C
Cooper B
Copake B
Copalis C
Copas C
Copeland C
Coplay D
Coral B
Corcega D
Corduroy B
Corkindale C
Corley C
Cornutt D
Corvallis B
Corwin B
Corydon C
Cossayuna C
Cotaco C
Coto C
Cottonwood C
Cougar C
Couparle D
Coupeville B
Courtland B
Courtney D
Couse C
Cove D
Coveland C
Coveytown C
Covington D
Dowden D
Cowiche B
Cowling B
Coxville D
Crago B
Craig C
Crandon B
Crane B
Craven C
Crawford D
Creal D
Creedmoor C
Cresbard C
Crescent B
Crestmore C
Crete D
Crevasse A
Crider B
Crockett D
Crofton B
Croghan B
Croom C
Crosby C
Crossville B
Croton D
Crow C
Crowder D
Crowley D
Crown B
Crystal B
Culleoka B
Cullo C
Culpeper B
Culvers C
Cumberland B
Curran C
Curtis B
Cushman B
Custer D
Cut Band B
Duthbert C
Cypremort C

Dade A
Daggett B
Dakota B
Dalbo B
Dale C
Dalhart B
Dalton C
Dana B
Dandridge C
Daniels B
Danley C
Dannemora C
Danvers C
Darien C
Darling C
Darnell C
Darret B
Darwin D
Davidson B
Davie B
Dawes C
Dayton D
Deary C
Decatur B
Deckerville D
Decorra B
Defiance D
[1]Dekalb B
Delanco B
Delfina C
Dell C
Dellrose B
Delphi B
Delpine D
Delray C
Del Rey C
Demers C
Denham D
Dennis C
Denny C
Denrock D
Denson C
Denton C
Depew C
Derby A
Descalabrado B
Deschutes A
De Soto C
Detour C
Detroit B
Dewart B
Dewey B
Dexter B
Diablo D
Dick A
Dickey A
Dickinson Fine
Sandy Loam A
Dickinson Loam B
Dickson C
Dill B
Dilldown B
Dillinger B
Dillon D
Dilman B
Dimmick D
Disco B
Dixmont B
Dodgeville
Deep Phase B
Dodgeville
Shallow Phase C
Doland B
Dominguito D
Dominic B
Donerail C
Donlonton C
Dorchester B
Dorsey D
Dos Cabezas B
Doty B
Dougherty B
Douglas B
Dover C
Dowellton D
Dowling D
Downs B
Doylestown D
Dragston C
Drake B
Dresden B
Dripping
Springs D
Drummer B
Drummond D
Drury B
Dryad C
Duane B
Dubbs B
Dubois C
Dubuque
Deep Phase B
Duffield B
Duffy C
Dukes A
Dulac C
Dunbar C
Duncan C
Duncannon B
Duncom D
Dundas C
Dundee C
Dune Sand A
Dunellen B
Dungeness B
Dunham B
Dunkirk B
Dunlap C
Dunmore C
Dinning D
Du Page B
Duplin B
Dupo C
Dupont D
Durant D
Durham B
Durkee C
[1]Dutchess B
Dutson C
Duval B
Dwight D
Dwyer A
Dyke B

Eakin B
Easton C
Eastonville A
Ebbert D
Ebbs B
Ebeys B
Eckman B
Ector C
Edalgo D
Eddy C
Eden C
Edenton C
Edge D
Edgeley C
Edgemont B
Edgewick A
Edgington C
Edina D
Edinburg C
Edisto C
Edith A
Edmonds D
Edna D
Edneyville B
Edom C
Edwards C
Eel C
Efland C
Egam C
Egeland B
Elfort C
Elbert D
Elburn B
Elco B
Eld B
Eldon C
Eldorado C
Elfrida C
Elioak B
Elk B
Elkina D
Elkinsville B
Eldton D
Ellery D
Elliber A
Ellington C
Elliott C
Ellis D
Ellison B
Ellsberry C
Ellsworth D
Elmo C
Elmore C
Elmwood C
Elsinboro B
Elsmere A
Elwha C
Emmert A
Emmet B
Emory B
Empey C
Empeyville C
Enders C
Enfield B
Englund D
Ennia B
Enon C
Ensenada C
Ensley D
Enstrom B
Enterprise A
Enumclaw B
Ephrata A
Epping D
Era B
Eram D
Erie C
Ernest C
Escondido C
Espinosa B
Esquatzel B
Essex C
Estacion B
Estelline B
Estevan C
Esterville B
Esto C
Etowah B
Ettrick D
Eubanks B
Eufaula A
Eulonia C
Eustis A
Eutaw D
Evans B
Evendale C
Everett A
Everson C
Ewing A
Exline D
Eylar D

Faceville B
Fahey B
Fairfax B
Fairhaven B
Fairhope C
Fairmount D
Fajardo C
Falaya C
Falcon B
Falkner D
Fall B
Fallbrook B
Fallsburg C
Fallsington D
Falun B